US009464764B2

(12) **United States Patent**
Hyde et al.

(10) **Patent No.: US 9,464,764 B2**
(45) **Date of Patent: Oct. 11, 2016**

(54) **DIRECT COOLING OF CLATHRATE FLOWING IN A PIPELINE SYSTEM**

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(73) Assignee: **Elwha LLC**

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1019 days.

(21) Appl. No.: **13/488,217**

(22) Filed: **Jun. 4, 2012**

(65) **Prior Publication Data**

US 2013/0319538 A1 Dec. 5, 2013

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/488,166, filed on Jun. 4, 2012, and a continuation-in-part of application No. 13/488,261, filed on Jun. 4, 2012.

(51) **Int. Cl.**
F17D 1/08 (2006.01)

(52) **U.S. Cl.**
CPC ***F17D 1/08*** (2013.01); *Y10T 137/0318* (2015.04); *Y10T 137/0391* (2015.04); *Y10T 137/6416* (2015.04); *Y10T 137/87265* (2015.04)

(58) **Field of Classification Search**
USPC 137/89, 110, 339, 340, 599.14; 166/52, 166/302; 299/3–7; 165/45, 104.26, 154
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,316,931 A * 5/1967 Elrod 137/339
3,514,274 A 5/1970 Cahn et al.
3,650,119 A * 3/1972 Sparling F16L 1/026 137/236.1
3,674,086 A * 7/1972 Foster 165/45
3,735,769 A 5/1973 Miller
3,756,268 A * 9/1973 Lefever et al. 137/340
3,906,972 A * 9/1975 Jensen et al. 406/197
3,943,965 A 3/1976 Matelena
3,975,167 A 8/1976 Nierman
4,266,958 A 5/1981 Cummings
4,776,181 A 10/1988 Maule
4,976,100 A * 12/1990 Lee 60/772
5,056,588 A * 10/1991 Carr 165/10

(Continued)

FOREIGN PATENT DOCUMENTS

WO WO 01/38781 A1 5/2001
WO WO 01/48367 A1 7/2001

OTHER PUBLICATIONS

Buried Treasure. The Why Files [online], Oct. 2000 [retrieved on Jul. 27, 2015]. Retrieved from the Internet: <URL:http://whyfiles.org/119nat_gas/3.html>.*

(Continued)

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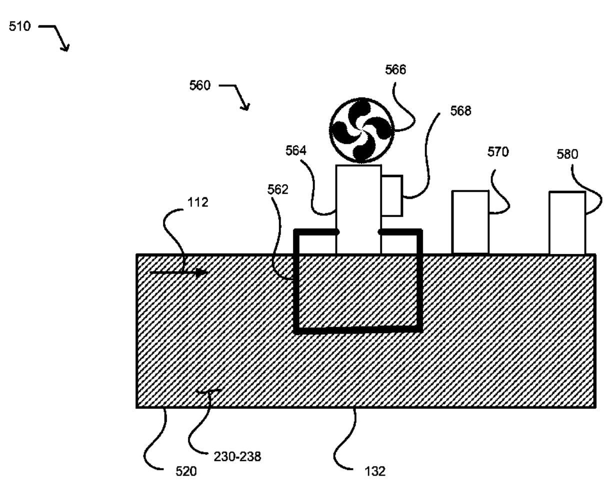
(57) **ABSTRACT**

Described embodiments include a system and a method. A described pipeline system includes a transportation conduit containing a gas hydrate flowing from a first geographical location to another geographical location. The pipeline system includes a cooling system in thermal contact with the flowing gas hydrate and maintaining the temperature of the flowing gas hydrate within a target temperature range predicted to maintain a selected stability of the flowing gas hydrate. In an embodiment, the pipeline system includes a controller configured to control a pressure or temperature of the flowing gas hydrate in response to a sensed pressure or temperature of the flowing gas hydrate.

23 Claims, 12 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

6,012,292	A	1/2000	Gulati et al.	
6,307,191	B1 *	10/2001	Waycuilis	219/687
6,350,928	B1	2/2002	Waycuilis et al.	
6,585,047	B2 *	7/2003	McClung, III	166/302
6,703,534	B2	3/2004	Waycuilis et al.	
6,774,276	B1	8/2004	Lund et al.	
7,958,939	B2	6/2011	Talley	
9,303,819	B2 *	4/2016	Hyde	F17D 1/08
2002/0120172	A1	8/2002	Waycuilis et al.	
2004/0187518	A1	9/2004	Laude Bousquet	
2005/0059846	A1	3/2005	Kohda et al.	
2005/0284612	A1 *	12/2005	Machiroutu	165/104.25
2006/0201180	A1	9/2006	Kidwell et al.	
2007/0062704	A1 *	3/2007	Smith	166/303
2008/0209916	A1	9/2008	White	
2008/0257315	A1 *	10/2008	Thomas	F02M 31/18 123/548
2008/0264099	A1	10/2008	Mock et al.	
2009/0035627	A1	2/2009	Tohidi et al.	
2009/0124520	A1	5/2009	Tohidi	
2009/0166032	A1 *	7/2009	Carr, Sr.	166/250.01
2009/0221451	A1	9/2009	Talley	
2010/0006291	A1	1/2010	Poorte	
2010/0145115	A1	6/2010	Lund et al.	
2010/0200237	A1	8/2010	Colgate et al.	
2010/0236634	A1	9/2010	Nuland et al.	
2011/0185623	A1	8/2011	Cooper et al.	
2011/0308625	A1	12/2011	Stoisits et al.	
2012/0070344	A1	3/2012	Carstens et al.	

OTHER PUBLICATIONS

Thermal Conductivity. HyperPhysics [online], Dec. 2009 [retrieved on Jul. 27, 2015]. Retrieved from the Internet: <URL:http://hyperphysics.phy-astr.gsu.edu/hbase/tables/thrcn.html>.*

PCT International Search Report; International App. No. PCT/US2013/042633; Oct. 8, 2013; pp. 1-2.

PCT International Search Report; International App. No. PCT/US2013/042625; Oct. 22, 2013; pp. 1-2.

"An Introduction to Natural Gas Hydrate/Clathrate: The Major Organic Carbon Reserve of the Earth", Journal of Petroleum Science and Engineering, 2007, pp. 1-8, vol. 56, Elsevier B.V.

Andersson, Vibeke et al., "Transporting Oil and Gas as Hydrate Slurries", 14th Int. Conf. on Slurry Handling and Pipeline Transport, Hydrotransport 14, Sep. 8-10, 1999, pp. 1-7, Maastricht, The Netherlands.

"Clathrate Compound", Wikipedia; printed on Apr. 11, 2012, pp. 1-3, located at: http://en.wikipedia.org/wiki/Clathrate.

Daimaru, Takamichi et al., "Energy Saving Potential for Natural Gas Hydrate Transportation", Prepr. Pap.-Am. Chem. Soc., Div. Fuel Chem, 2004, vol. 49, No. 1, pp. 190-191.

Gudmundsson, J.S. et al., "Frozen Hydrate for Transport of Natural Gas", 2nd International Conference on Natural Gas Hydrate, Jun. 2-6, 1996, pp. 1-8, Toulouse, France.

Iwata, Zensuke et al., "Heat Pipe Local Cooling System Applied for 145 KV Transmission Lines in Copenhagen", 1991, pp. 52-60, IEEE.

Javanmardi, J. et al., "Natural Gas Hydrate, an Alternative for Transportation of Natural Gas", printed on Feb. 24, 2004, pp. 1-6, located at: http://www.ipt.ntnu.no/~ngh/library/paper2.html.

Javanmardi, J. et al., "Economic Evaluation of Natural Gas Hydrate Gas Transportation", Applied Thermal Engineering, Aug. 2005, pp. 1708-1723, vol. 25, Issue 11-12, Elsevier Ltd.

Kanda, H. "Economic Study on Natural Gas Transportation with Natural Gas Hydrate (NGH) Pellets", 23rd World Gas Conference, 2006, pp. 1-11, Amsterdam.

"Methane Hydrate: A Surprising Compound", printed on Apr. 23, 2012, pp. 1-6, Science & Technology Review, located at: https://www.llnl.gov/str/Durham.html?pagewanted=all.

PCT International Search Report; International App. No. PCT/US2013/042643; Dec. 13, 2013;pp. 1-2.

Shi, Guohua et al., "Prospects of Natural Gas Storage and Transportation Using Hydrate Technology in China", ICIEA, 2009, pp. 530-534, IEEE.

Sloan, E. Dendy, Jr., "Fundamental Principles and Applications of Natural Gas Hydrates", Nature, Nov. 20, 2003, pp. 353-359, vol. 426, Nature Publishing Group.

Thomas, Sydney et al., "Review of Ways to Transport Natural Gas Energy From Countries Which Do Not Need the Gas for Domestic Use", Energy, 2003, pp. 1461-1477, vol. 28, Elsevier Ltd.

"Transport of Natural Gas Hydrates (NGH)", Jul. 2011, pp. 1-2, located at: http://www.marathononoil.com/content/inline-images/marathon_com/about_us/technology/NatGasHydrates_Nobio_FINAL.pdf.

Turner, Doug et al., "Hydrate Inhibition Via Cold Flow—No Chemicals or Insulation", Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008), Jul. 6-10, 2008, pp. 1-12, Vancouver, Canada.

* cited by examiner

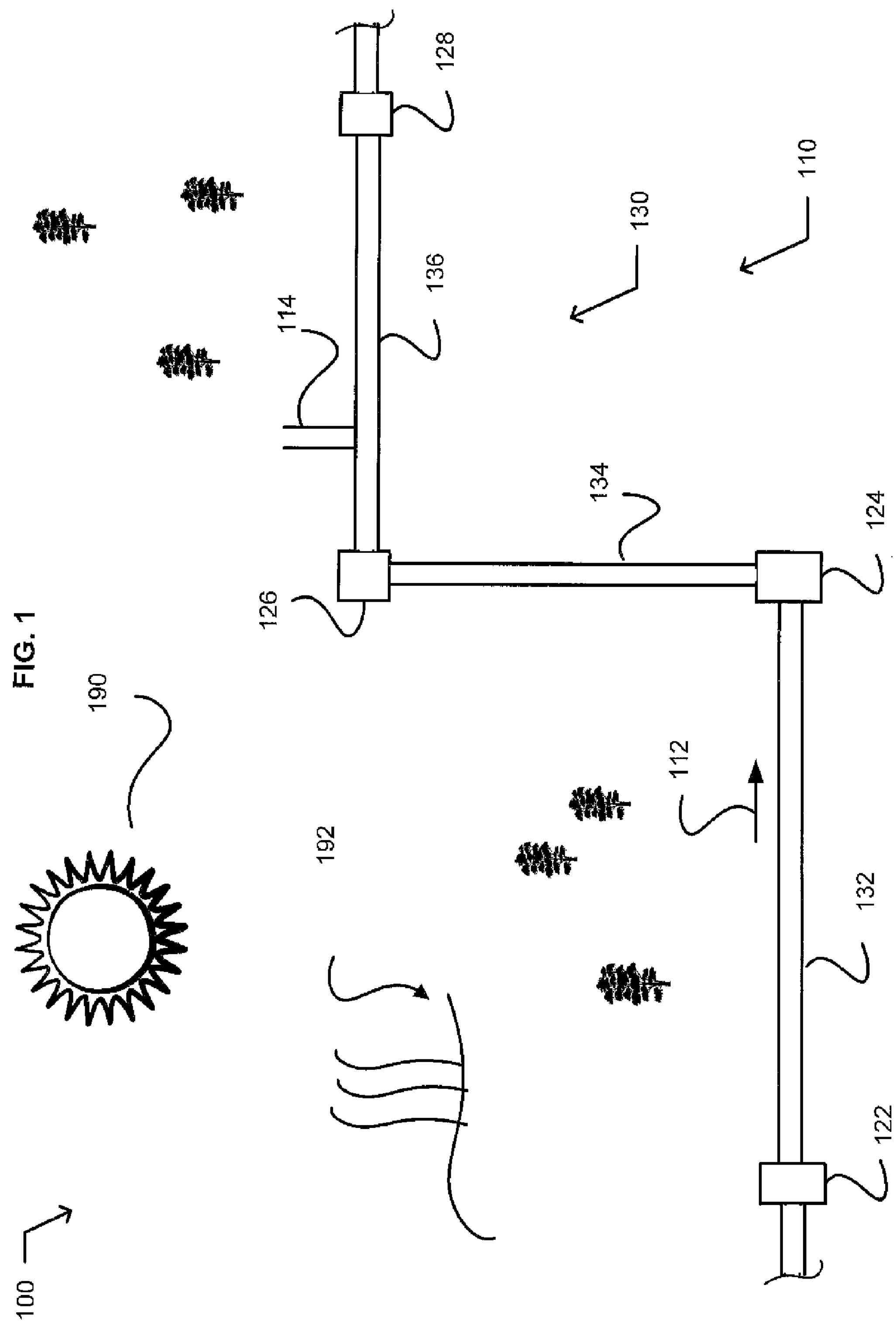


FIG. 1

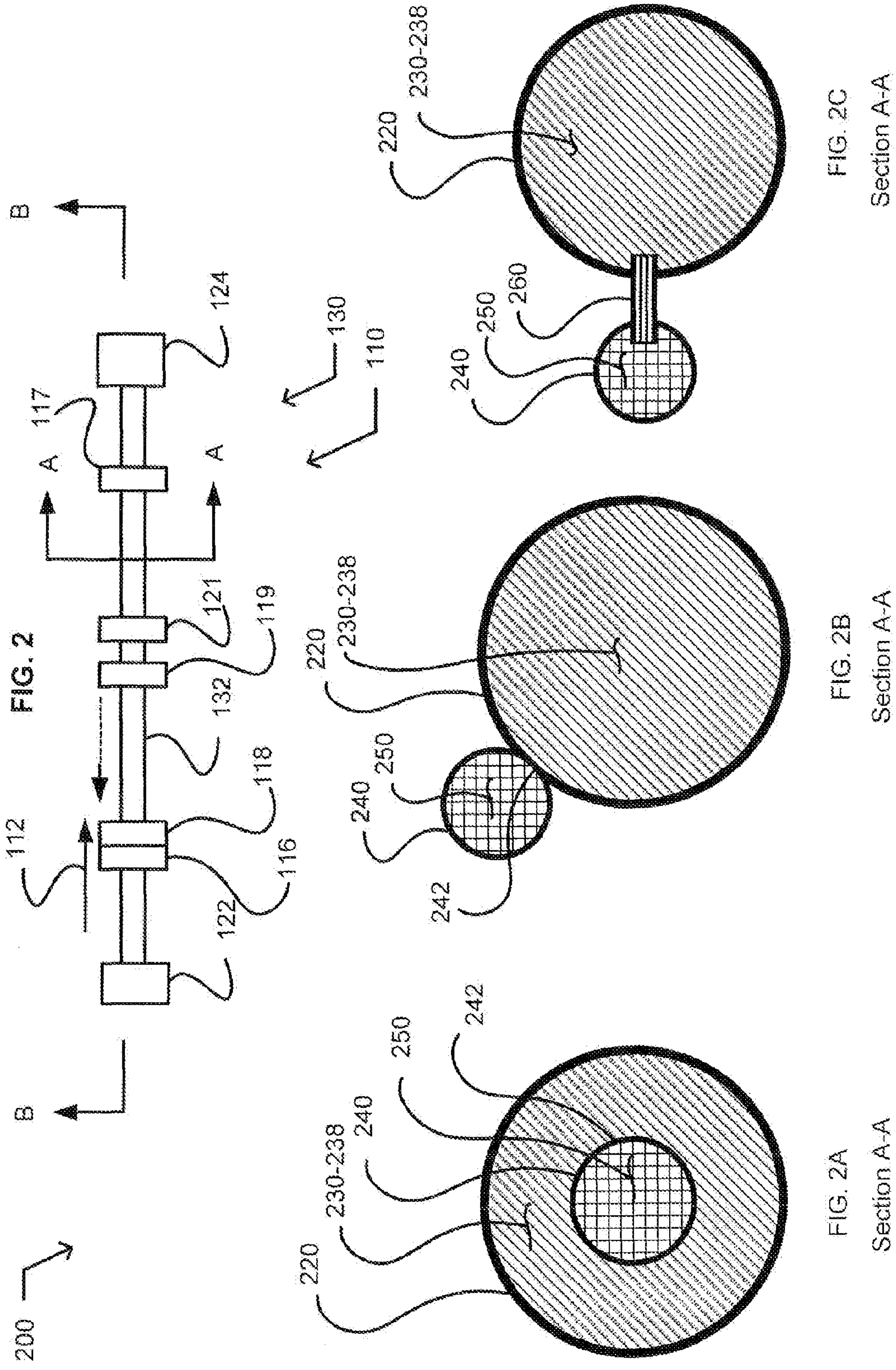


FIG. 2
200
B
B
A
A
112
122
116
118
132
119
121
117
124
130
110
220
230-238
240
250
242
260
FIG. 2A
Section A-A
FIG. 2B
Section A-A
FIG. 2C
Section A-A

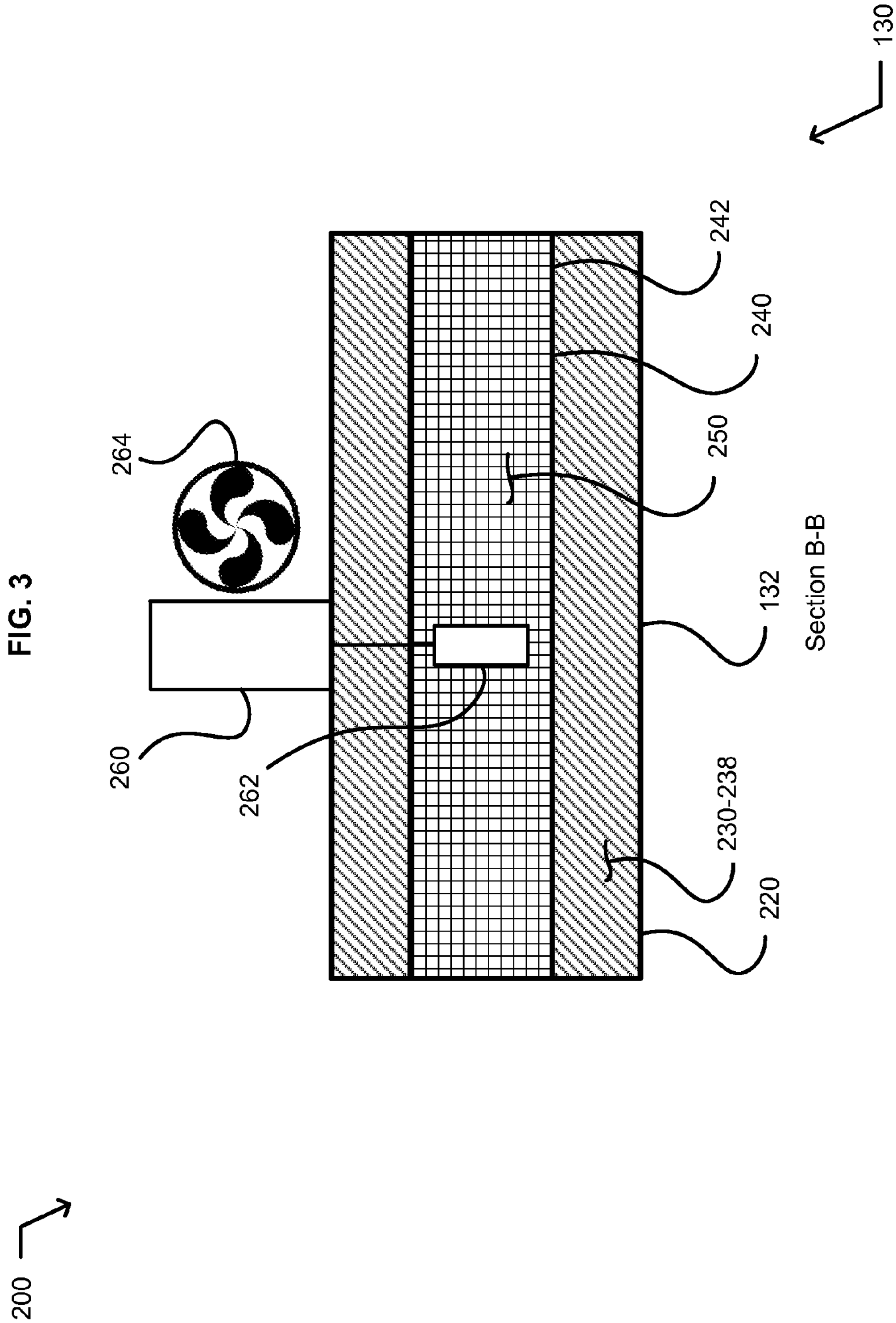


FIG. 3

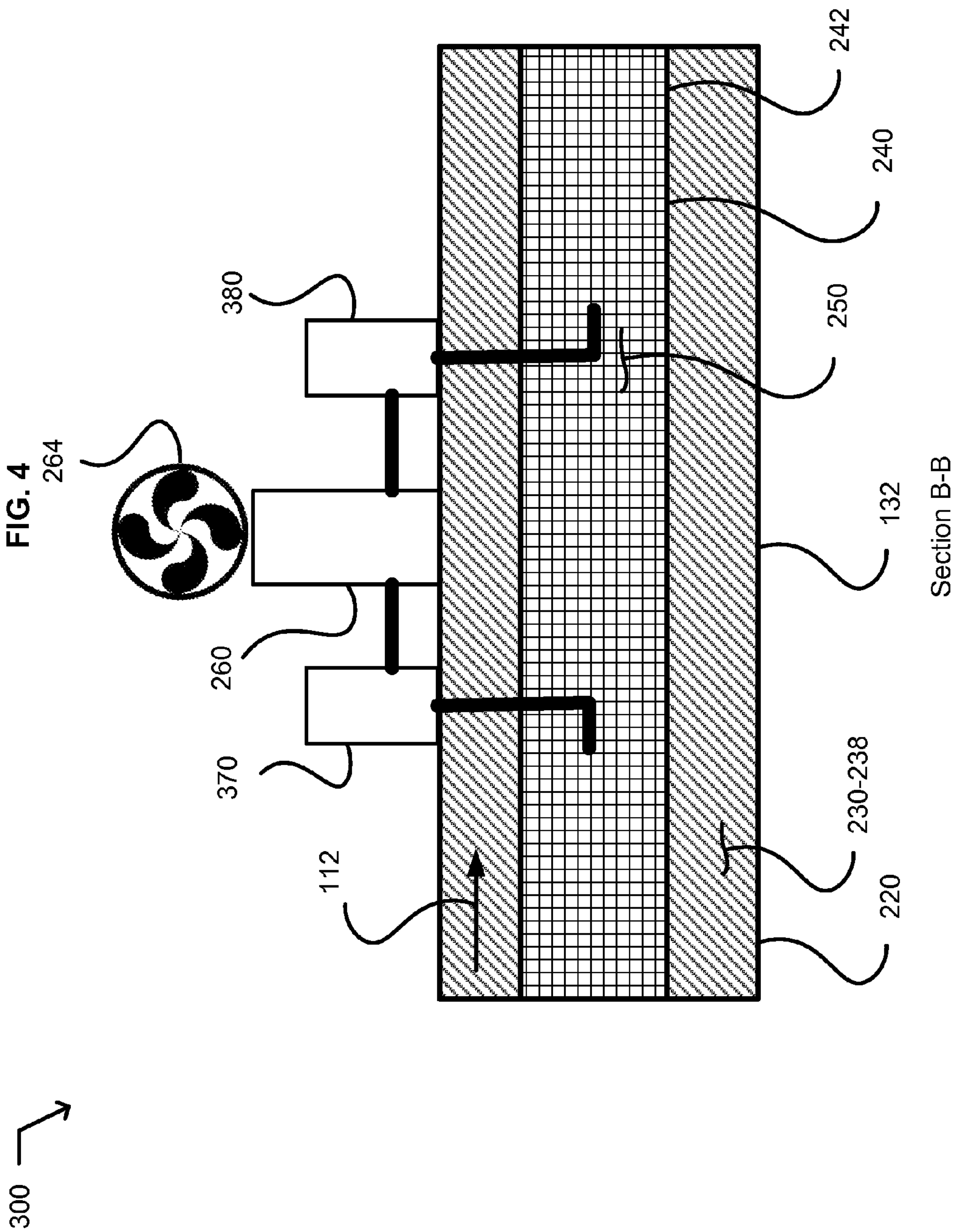
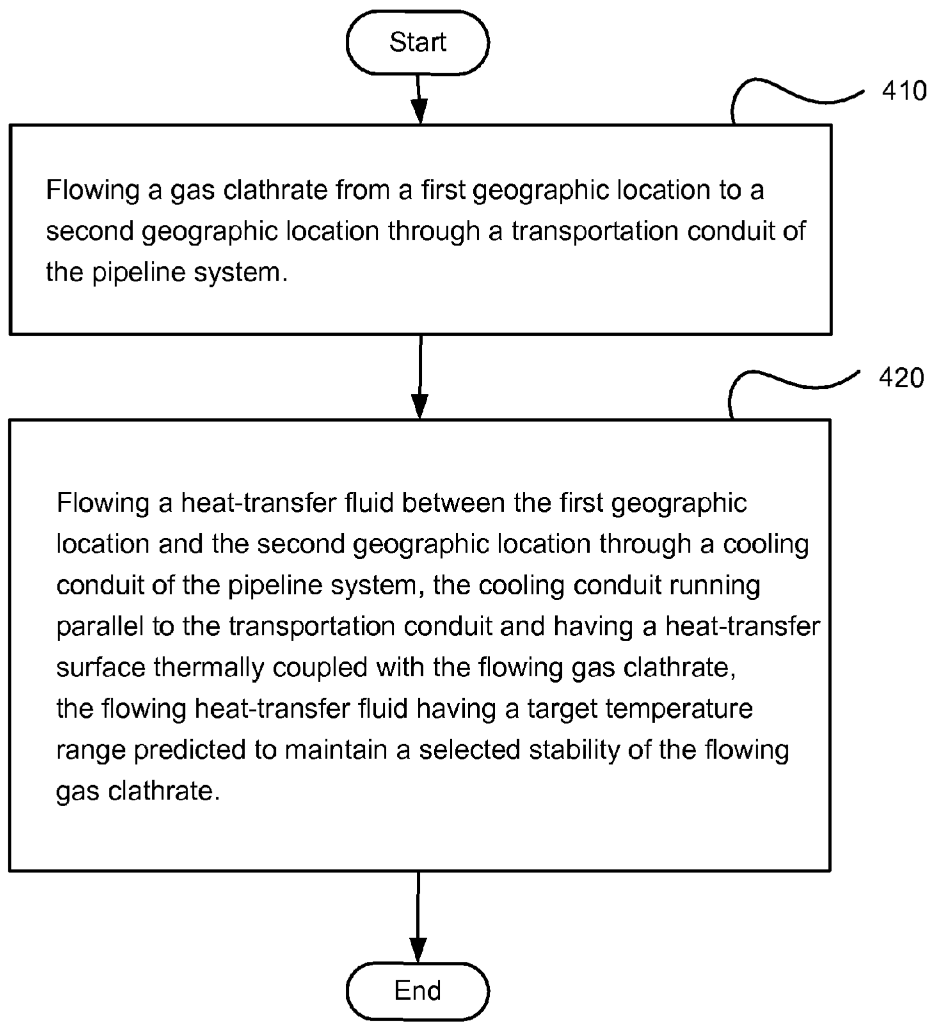


FIG. 4

400

FIG. 5


Start
410
Flowing a gas clathrate from a first geographic location to a second geographic location through a transportation conduit of the pipeline system.
420
Flowing a heat-transfer fluid between the first geographic location and the second geographic location through a cooling conduit of the pipeline system, the cooling conduit running parallel to the transportation conduit and having a heat-transfer surface thermally coupled with the flowing gas clathrate, the flowing heat-transfer fluid having a target temperature range predicted to maintain a selected stability of the flowing gas clathrate.
End

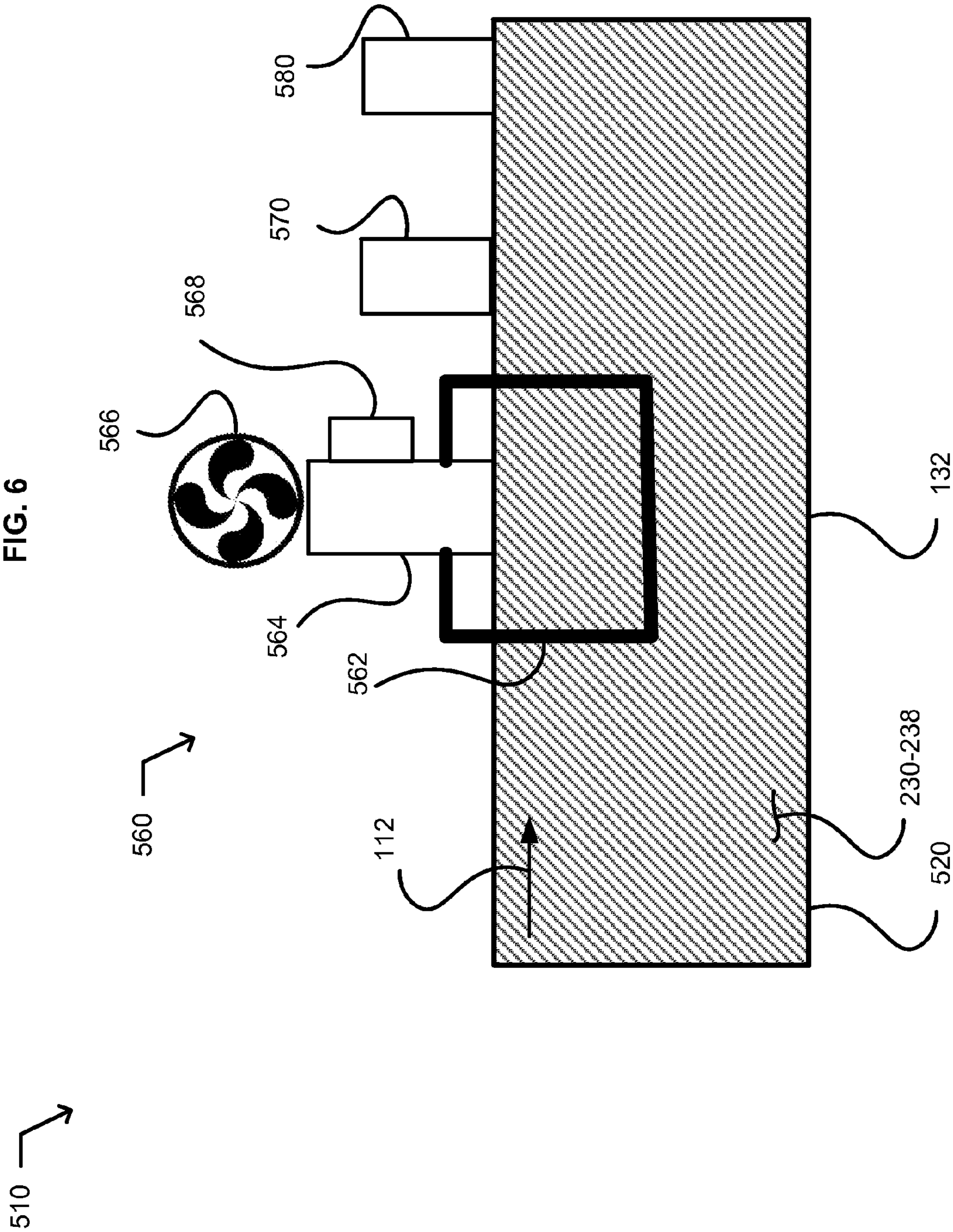


FIG. 6

FIG. 7

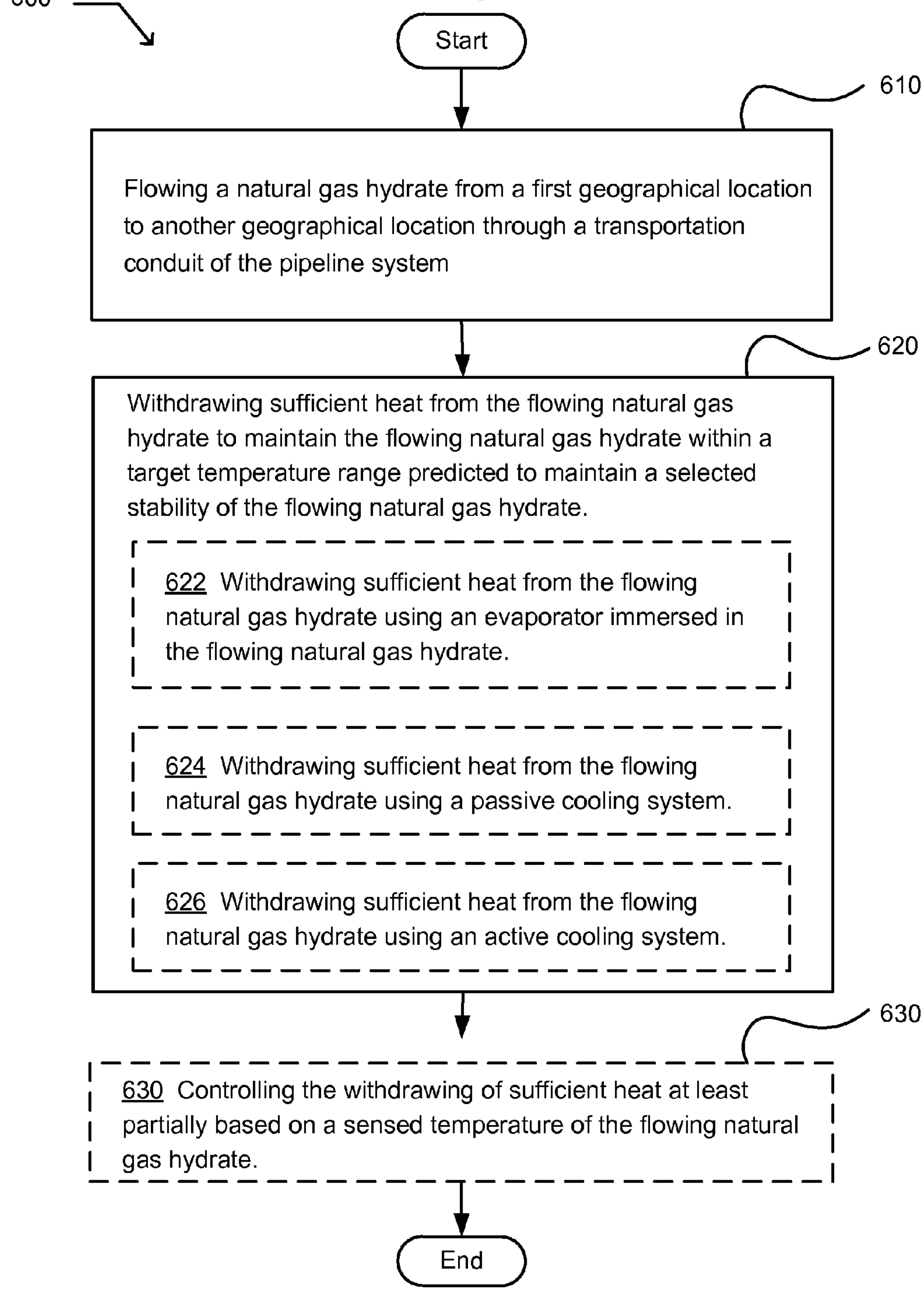
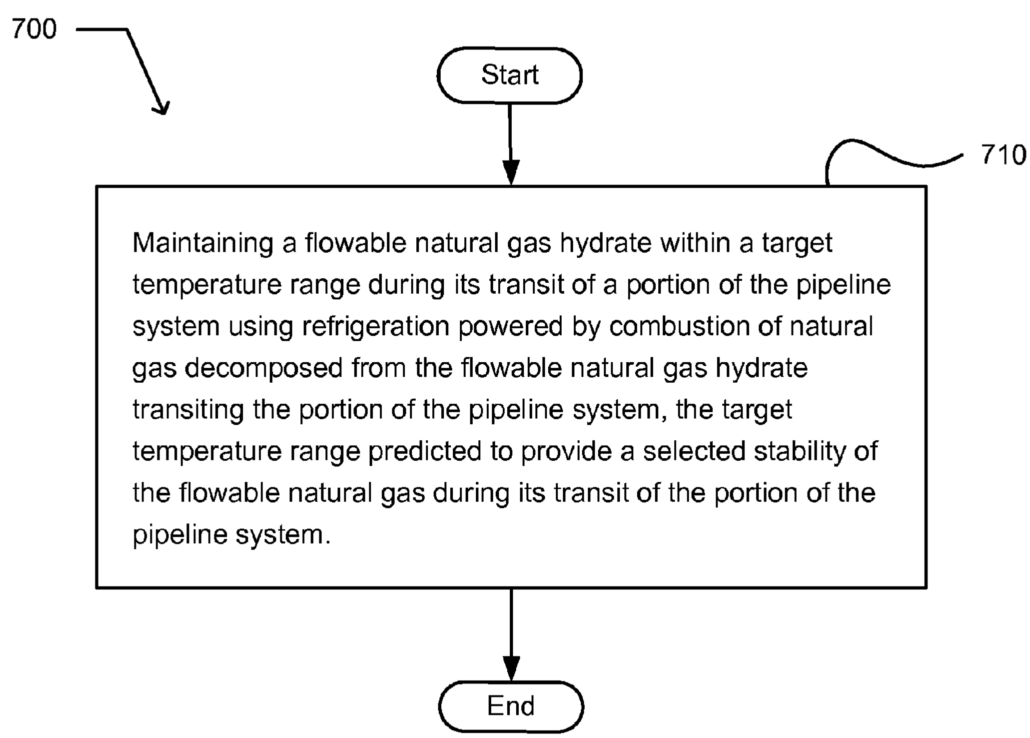

600
Start
610
Flowing a natural gas hydrate from a first geographical location to another geographical location through a transportation conduit of the pipeline system
620
Withdrawing sufficient heat from the flowing natural gas hydrate to maintain the flowing natural gas hydrate within a target temperature range predicted to maintain a selected stability of the flowing natural gas hydrate.
622 Withdrawing sufficient heat from the flowing natural gas hydrate using an evaporator immersed in the flowing natural gas hydrate.
624 Withdrawing sufficient heat from the flowing natural gas hydrate using a passive cooling system.
626 Withdrawing sufficient heat from the flowing natural gas hydrate using an active cooling system.
630
630 Controlling the withdrawing of sufficient heat at least partially based on a sensed temperature of the flowing natural gas hydrate.
End

FIG. 8


700
Start
710
Maintaining a flowable natural gas hydrate within a target temperature range during its transit of a portion of the pipeline system using refrigeration powered by combustion of natural gas decomposed from the flowable natural gas hydrate transiting the portion of the pipeline system, the target temperature range predicted to provide a selected stability of the flowable natural gas during its transit of the portion of the pipeline system.
End

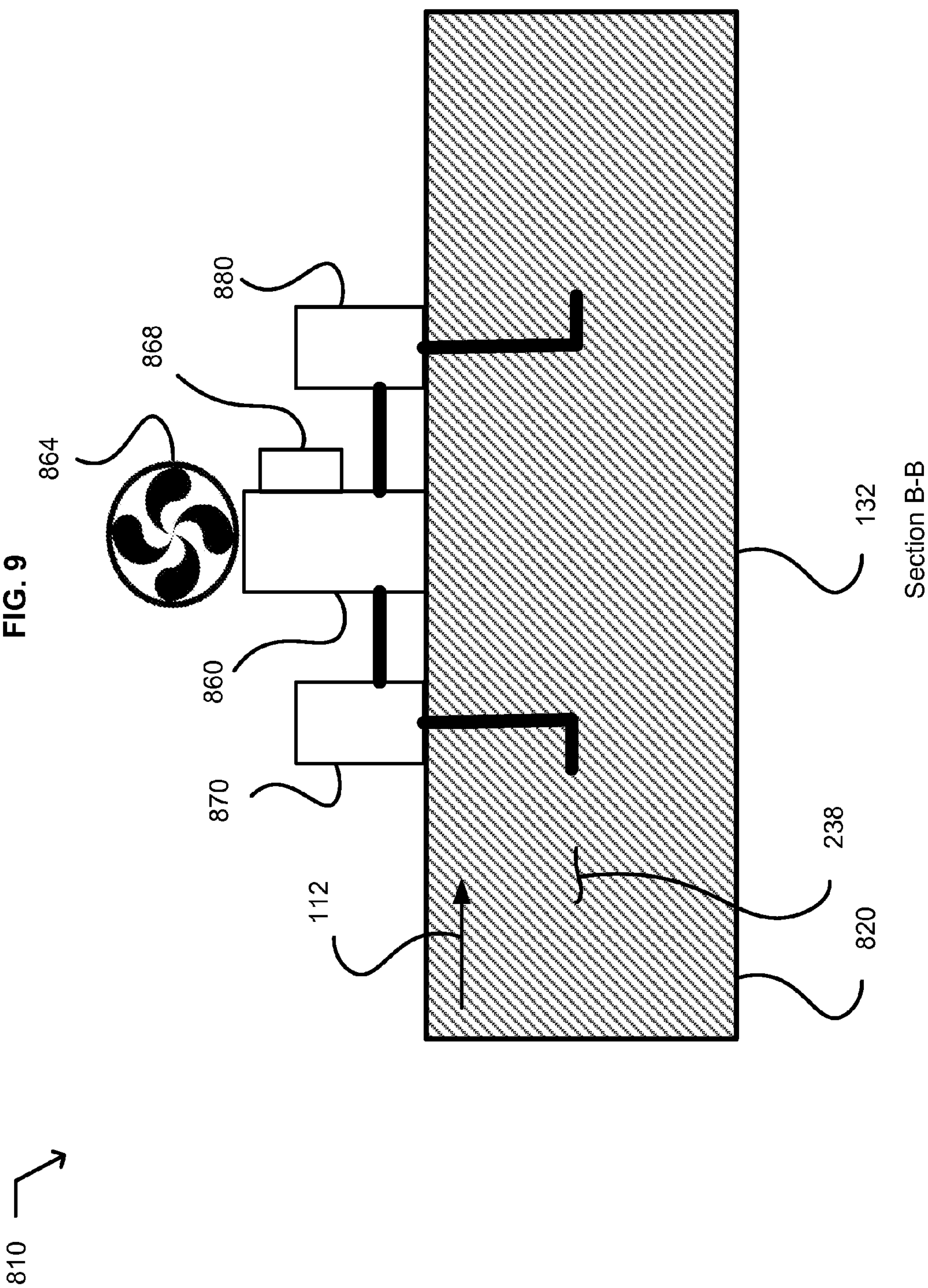
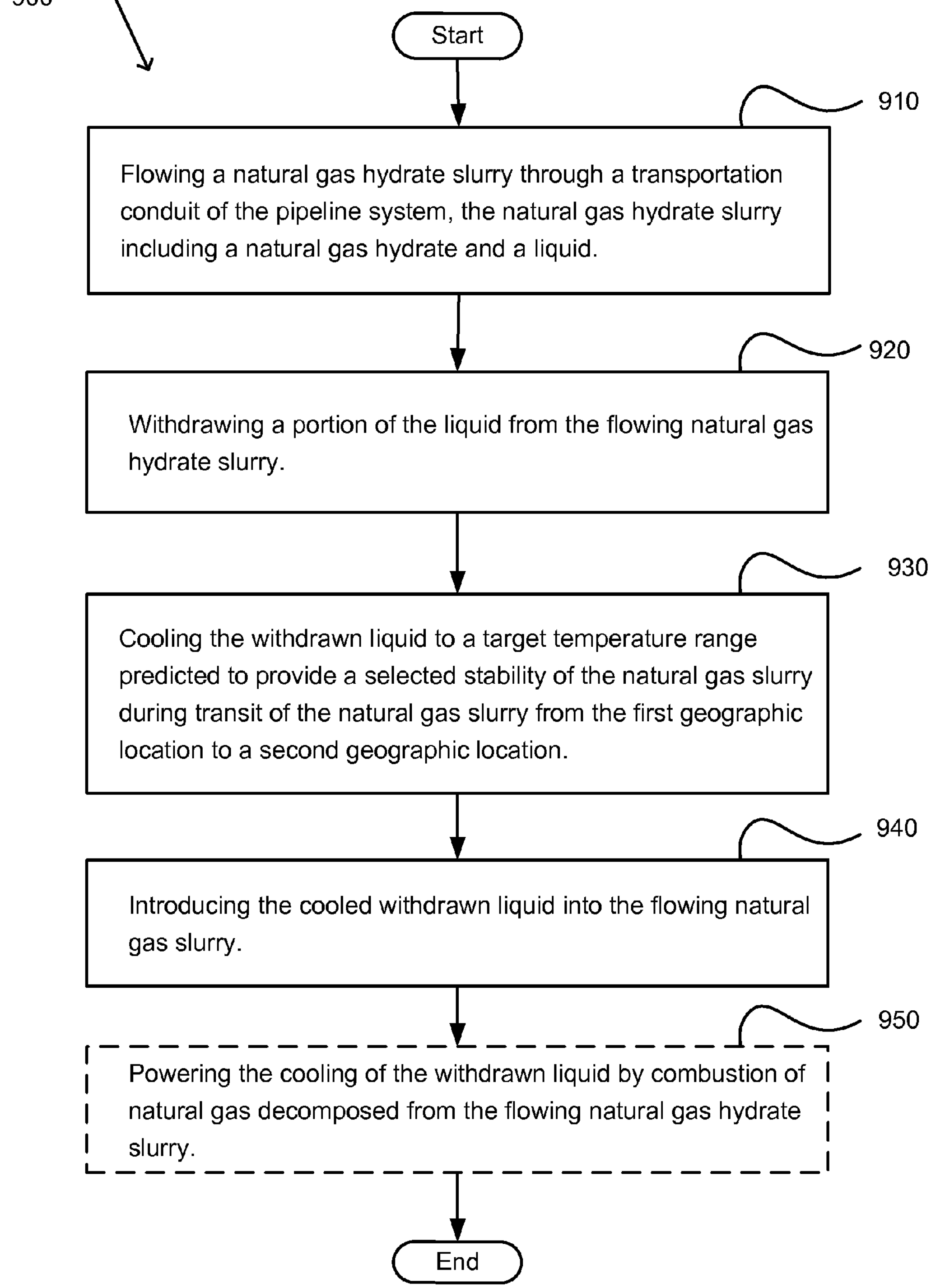


FIG. 9

FIG. 10


900
Start
910
Flowing a natural gas hydrate slurry through a transportation conduit of the pipeline system, the natural gas hydrate slurry including a natural gas hydrate and a liquid.
920
Withdrawing a portion of the liquid from the flowing natural gas hydrate slurry.
930
Cooling the withdrawn liquid to a target temperature range predicted to provide a selected stability of the natural gas slurry during transit of the natural gas slurry from the first geographic location to a second geographic location.
940
Introducing the cooled withdrawn liquid into the flowing natural gas slurry.
950
Powering the cooling of the withdrawn liquid by combustion of natural gas decomposed from the flowing natural gas hydrate slurry.
End

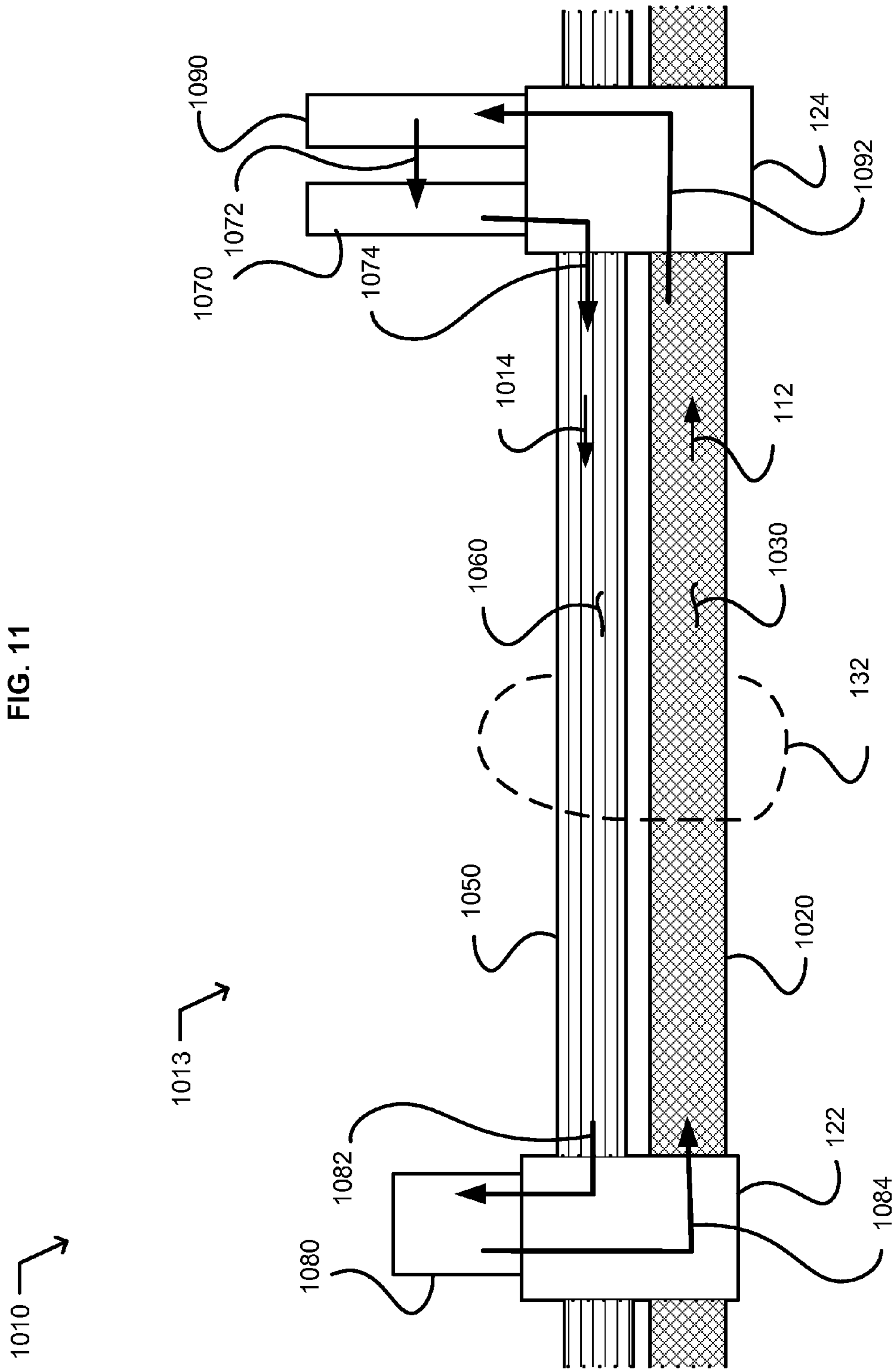
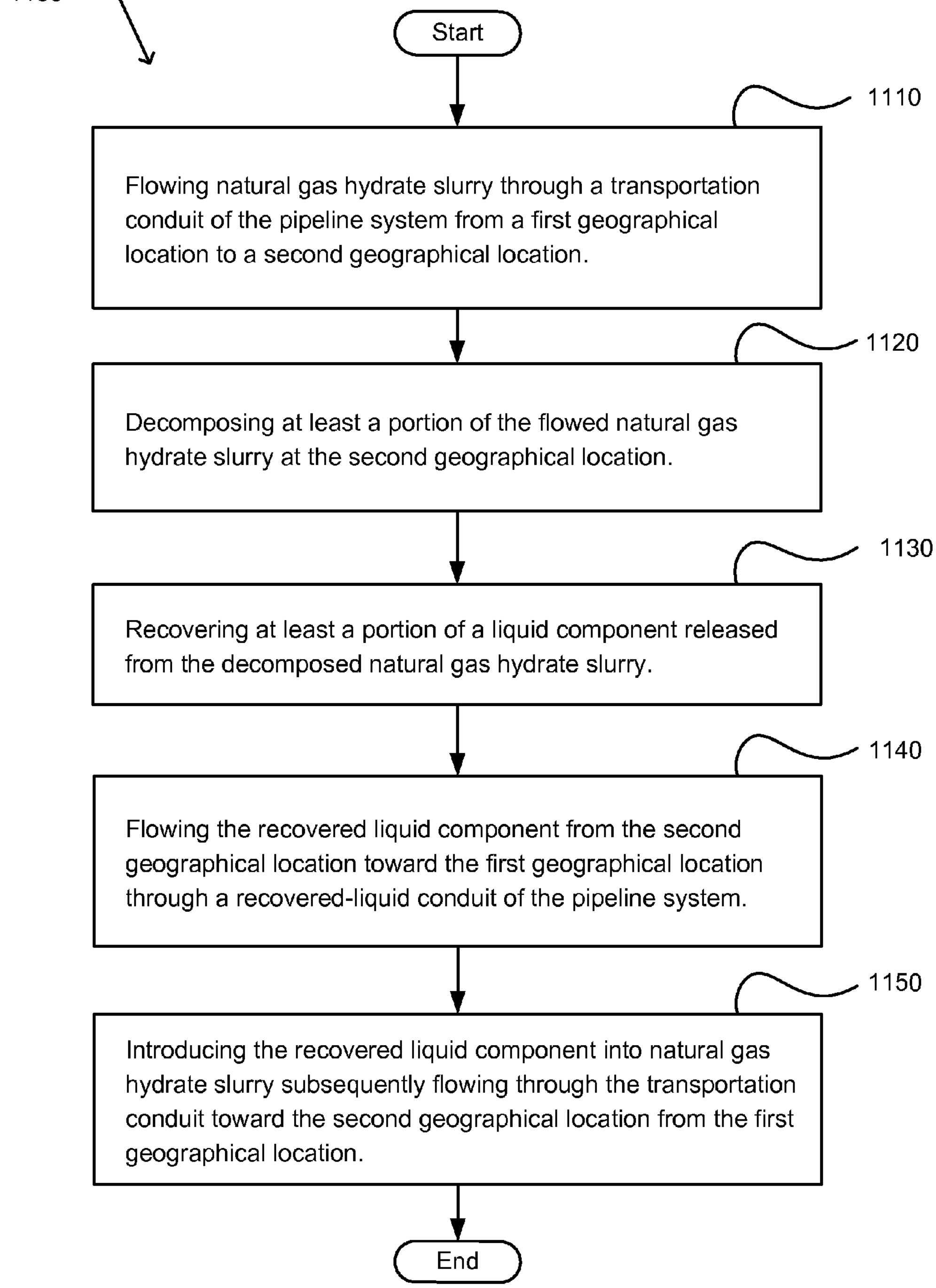

1090
1072
1070
1074
124
1092
1014
112
1060
1030
132
1050
1020
1013
1082
122
1080
1084
1010

FIG. 11

FIG. 12


1100
Start
1110
Flowing natural gas hydrate slurry through a transportation conduit of the pipeline system from a first geographical location to a second geographical location.
1120
Decomposing at least a portion of the flowed natural gas hydrate slurry at the second geographical location.
1130
Recovering at least a portion of a liquid component released from the decomposed natural gas hydrate slurry.
1140
Flowing the recovered liquid component from the second geographical location toward the first geographical location through a recovered-liquid conduit of the pipeline system.
1150
Introducing the recovered liquid component into natural gas hydrate slurry subsequently flowing through the transportation conduit toward the second geographical location from the first geographical location.
End

DIRECT COOLING OF CLATHRATE FLOWING IN A PIPELINE SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is related to and claims the benefit of the earliest available effective filing date(s) from the following listed application(s) (the "Related Applications") (e.g., claims earliest available priority dates for other than provisional patent applications or claims benefits under 35 USC §119(e) for provisional patent applications, for any and all parent, grandparent, great-grandparent, etc. applications of the Related Application(s)).

RELATED APPLICATIONS

For the purposes of the USPTO extra-statutory requirement, the present application constitutes a continuation in part of U.S. Ser. No. 13/488,166, entitled CHILLED CLATHRATE TRANSPORTATION SYSTEM, naming Roderick A. Hyde and Lowell L. Wood, Jr., as inventors, filed Jun. 4, 2012, which is currently co-pending, or is an application of which a currently co-pending application is entitled to the benefit of the filing date.

For the purposes of the USPTO extra-statutory requirement, the present application constitutes a continuation in part of U.S. Ser. No. 13/488,261, entitled FLUID RECOVERY IN CHILLED CLATHRATE TRANSPORTATION SYSTEMS, naming Roderick A. Hyde and Lowell L. Wood, Jr., as inventors, filed Jun. 4, 2012, which is currently co-pending, or is an application of which a currently co-pending application is entitled to the benefit of the filing date.

The United States Patent Office (USPTO) has published a notice to the effect that the USPTO's computer programs require that patent applicants reference both a serial number and indicate whether an application is a continuation or continuation-in-part. Stephen G. Kunin, Benefit of Prior-Filed Application, USPTO Official Gazette Mar. 18, 2003. The present Applicant Entity (hereinafter "Applicant") has provided above a specific reference to the application(s) from which priority is being claimed as recited by statute. Applicant understands that the statute is unambiguous in its specific reference language and does not require either a serial number or any characterization, such as "continuation" or "continuation-in-part," for claiming priority to U.S. patent applications. Notwithstanding the foregoing, Applicant understands that the USPTO's computer programs have certain data entry requirements, and hence Applicant is designating the present application as a continuation-in-part of its parent applications as set forth above, but expressly points out that such designations are not to be construed in any way as any type of commentary or admission as to whether or not the present application contains any new matter in addition to the matter of its parent application(s).

All subject matter of the Related Applications and of any and all parent, grandparent, great-grandparent, etc. applications of the Related Applications is incorporated herein by reference to the extent that such subject matter is not inconsistent herewith.

SUMMARY

For example, and without limitation, an embodiment of the subject matter described herein includes a pipeline system. The pipeline system includes a transportation conduit containing a gas hydrate flowing from a first geographical location to another geographical location. The pipeline system includes a cooling system in thermal contact with the flowing gas hydrate and maintaining the temperature of the flowing gas hydrate within a target temperature range predicted to maintain a selected stability of the flowing gas hydrate.

In an embodiment, the pipeline system includes a pump system urging the flowing gas hydrate through at least the portion of the transportation conduit. In an embodiment, the pipeline system includes a pressure sensor responsive to a pressure of the flowing gas hydrate. In an embodiment, the pipeline system includes a temperature sensor responsive to a temperature of the flowing gas hydrate. In an embodiment, the pipeline system includes a controller configured to control a pressure or temperature of the flowing gas hydrate in response to a sensed pressure or temperature of the flowing gas hydrate.

For example, and without limitation, an embodiment of the subject matter described herein includes pipeline system. The pipeline system includes a transportation conduit configured to contain a natural gas hydrate flowing from a first geographic location to a second geographic location. The pipeline system includes a cooling system configured to cool the contained and flowing natural gas hydrate to a target temperature range predicted to maintain a selected stability of the flowing natural gas hydrate.

In an embodiment, the pipeline system includes a cooling system controller coupled with the cooling system and configured to regulate cooling of the flowable natural gas hydrate by the cooling system. In an embodiment, the pipeline system includes a pressure controller configured to regulate pressure of the flowable natural gas hydrate contained within the portion of the transportation conduit. In an embodiment, the pipeline system includes an insulating material thermally separating the transportation conduit from the ambient temperature surrounding the transportation conduit of the pipeline system. In an embodiment, the pipeline system includes a pumping system configured to urge the flowable natural gas hydrate through at least the portion of the transportation conduit. In an embodiment, the pipeline system includes a pressure sensor responsive to a pressure of the flowable gas hydrate. In an embodiment, the pipeline system includes a temperature sensor responsive to a temperature of the flowable gas hydrate.

For example, and without limitation, an embodiment of the subject matter described herein includes a method implemented in a pipeline transportation system. The method includes flowing a natural gas hydrate from a first geographical location to another geographical location through a transportation conduit of the pipeline system. The method includes withdrawing sufficient heat from the flowing natural gas hydrate to maintain the flowing natural gas hydrate within a target temperature range predicted to maintain a selected stability of the flowing natural gas hydrate. In an embodiment, the method includes controlling the withdrawing of sufficient heat at least partially based on a sensed temperature of the flowing natural gas hydrate.

For example, and without limitation, an embodiment of the subject matter described herein includes a method implemented in a pipeline transportation system. The method includes maintaining a flowable natural gas hydrate within a target temperature range during its transit of a portion of the pipeline system using refrigeration powered by combustion of natural gas decomposed from the flowable natural gas hydrate transiting the portion of the pipeline system. The target temperature range is predicted to provide a selected

stability of the flowable natural gas during its transit of the portion of the pipeline system.

The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features described above, further aspects, embodiments, and features will become apparent by reference to the drawings and the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an example environment **100** in which embodiments may be implemented;

FIG. **2** illustrates an example environment **200** in which embodiments may be implemented;

FIG. **3** illustrates an alternative embodiment **200** of the pipeline system **110** and the pipeline **130** illustrated in FIGS. **1-2**;

FIG. **4** illustrates an alternative embodiment **300** of the pipeline system **110** and the pipeline **130** illustrated in FIGS. **1-2**;

FIG. **5** illustrates an example operational flow **400** implemented in a pipeline system;

FIG. **6** illustrates an example embodiment of a pipeline system **510** in which embodiments may be implemented;

FIG. **7** illustrates an example operational flow **600** implemented in a pipeline transportation system;

FIG. **8** illustrates an example operational flow **700** implemented in a pipeline transportation system;

FIG. **9** illustrates an example embodiment of a pipeline system **810** that transports flowable natural gas hydrate slurries;

FIG. **10** illustrates an example operational flow **900** implemented in a pipeline system that transports flowable natural gas hydrate slurries from a first geographical location and a second geographical location;

FIG. **11** illustrates an example pipeline system **1010** in which embodiments may be implemented; and

FIG. **12** illustrates an example operational flow **1100** implemented in a pipeline system that transports flowable natural gas hydrate slurries from a first geographical location to second geographical location.

DETAILED DESCRIPTION

In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrated embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here.

FIG. **1** illustrates an example environment **100** in which embodiments may be implemented. The environment includes a pipeline system **110** transporting or configured to transport a natural gas hydrate from one geographic location to another geographic location. For example, in an embodiment, a first geographic location **122** may be a city, such as Seattle, and a second geographic location **124** may be another city, such as Tacoma, Wash. A third geographic location **126** may be a location of a pumping station or other pipeline machinery, a pipeline related structure, or another city. For example, the third geographic location may be a location between Tacoma and Olympia, or a geographic location between Olympia and Portland, Oreg. For example, in an embodiment, the first geographic location **122**, the second geographic location **124**, the third geographic location **126**, and a fourth location **128** may each be about a mile apart along the pipeline system. For example, the pipeline system may include a transcontinental pipeline system, interstate pipeline system, intrastate pipeline system, city to city pipeline system, or a portion of the distance between these locations. The environment also includes the sun **190** heating air or soil proximate to the pipeline system to an ambient temperature **192**.

The pipeline system **110** includes a pipeline **130**. The pipeline is illustrated has having multiple segments, illustrated as segment **132**, segment **134**, and segment **136**.

FIG. **2** illustrates an example environment **200** in which embodiments may be implemented. The environment illustrates the segment **132** of the pipeline **130** running between geographic location **122** and **124**. FIGS. **2A-2C** illustrate several alternative embodiments of the pipeline at cross-section A-A. In these illustrated alternative embodiments, the pipeline includes a transportation conduit **220** containing a natural gas hydrate **234** flowing in direction **112** from the first geographic location **122** to the second geographic location **124**. In these illustrated alternative embodiments, the pipeline includes a cooling conduit **240** running parallel to the transportation conduit, having a heat-transfer surface **242** thermally coupled with the flowing natural gas hydrate, and containing a heat-transfer fluid **250** flowing between the first geographic location and the second geographic location. For example, the heat-transfer fluid may include a gas, a liquid, a slurry containing a solid undergoing a phase change to a liquid, or a liquid undergoing a phase change to a gas. The flowing heat-transfer fluid has a target temperature range predicted to maintain a selected stability of the flowing natural gas hydrate.

Natural gas is a gaseous fossil fuel consisting primarily of methane but often including significant quantities of ethane, propane, butane, pentane and heavier hydrocarbons. Natural gas produced from subterranean formations may also contain undesirable components such as carbon dioxide, nitrogen, helium and hydrogen sulfide. The undesirable components are usually removed before the natural gas is used as a fuel.

For example, fluids produced from a conventional hydrocarbon reservoir may be transported to a production facility, such as located on an offshore platform or on land. The produced fluid may be separated by separation apparatus into predominantly water, oil, and gas phases. The gas may be treated using a conventional gas treatment apparatus to remove contaminants such as CO_2 and H_2S. The treated gas may then be compressed and exported such as by using a compressor. The compressed gas may be introduced into a pipeline or shipped as compressed natural gas in a tanker. Alternatively, the natural gas may be liquefied and shipped by tanker or else converted by a gas-to-liquids process into a liquid product. Alternatively, the treated gas then may be formed in a natural gas hydrate and introduced into a pipeline or shipped in a tanker.

Clathrates are crystalline compounds defined by the inclusion of a "guest" molecule within a solid lattice of a host molecule. Gas clathrates are a subset of clathrate wherein the "guest" molecule is a gas at or near ambient temperatures and pressures. One of the most common varieties of clathrates is that where the host molecule is water. These are referred to as clathrate hydrates (often simply as "hydrates"). Clathrate hydrates are crystalline compounds defined by the inclusion of a guest molecule within a hydrogen bonded water lattice. Quantum physical forces such as van der Waals forces and hydrogen bonding are involved in creating and maintaining these clathrate hydrate structures. Gas hydrates are a subset of clathrate hydrates wherein the "guest" molecule is a gas at or near ambient temperatures and pressures. Such gases include methane, propane, carbon dioxide, hydrogen and many others. Natural gas hydrates (clathrate hydrates of natural gases) form when water and certain low molecular weight hydrocarbon molecules (e.g., those commonly found in "natural gas") are brought together under suitable conditions of relatively high pressure and low temperature. The primary guest molecule in natural gas hydrates is generally methane, but natural gas hydrates can also contain other species such as ethane, propane, etc.

Gas hydrates are defined by four primary physical characteristics: an ability to adsorb large amounts of guest molecules within a hydrogen bonded lattice; an ability to separate gas mixtures based on the preferential formation of one gas hydrate over another; a large latent heat of formation that is similar to that of ice, but dependent on the specific guest molecule and additives; and a formation temperature generally higher than that required to convert water to ice. Under these conditions the 'host' water molecules will form a cage or lattice structure capturing a "guest" gas molecule inside. Large quantities of gas are closely packed together by this mechanism. For example, a cubic meter of methane hydrate contains 0.8 cubic meters of water and up to 172 cubic meters of methane gas. While the most common clathrate on earth is methane hydrate, other gases also form hydrates including hydrocarbon gases such as ethane and propane as well as non-hydrocarbon gases such as H_2, CO_2 and H_2S. While many of the embodiments discusses herein refer to natural gas hydrates, the scope of this disclosure encompasses the transportation and cooling of other gas hydrates, such as those containing CO_2, H_2, and other low molecular weight hydrocarbons.

Gas hydrates are stable only under specific pressure-temperature conditions. Under the appropriate pressure, they can exist at temperatures significantly above the freezing point of water. The maximum temperature at which gas hydrate can exist depends on pressure and gas composition. For a given composition, the stability region for a gas hydrate can be represented as a region on a two dimensional pressure-temperature phase diagram; the gas hydrate is stable for pressure-temperature values within specified regions of the phase diagram, and unstable outside of these regions. The boundary between regions where the hydrate is and is not stable can be described as a function of pressure versus temperature, or equivalently, as a function of temperature versus pressure. For example, methane plus water at 600 psia forms hydrate at 41° F., while at the same pressure, methane+1% propane forms a gas hydrate at 49° F. Hydrate stability can also be influenced by other factors, such as salinity.

Natural gas hydrate slurry (separate or loosely aggregated hydrate particles which are suspended in a carrier fluid) can be formed by mixing a clathrate hydrate forming natural gas and water at low temperature and high pressure in a manner designed to maximize the surface contact area between the two. Recent published and/or patented art has identified and defined new mechanisms and potential mechanisms by which formation of natural gas hydrates can be made significantly more efficient. Such art includes the use of certain formation catalysts such as surfactants, hydrotropes, H-hydrate promoters, and activated carbon, which increase the efficiency of clathrate hydrate formation as well as various approaches to increase the rate of thermal transfer.

In an embodiment, the flowing natural gas hydrate **234** includes a natural gas hydrate able to flow, capable of flowing, or being flowed through the transportation conduit **220**. For example, flowing may include a capability of a liquid or loose particulate solid to move by flow. For example, flowing may be assisted by pumping, gravity, or pressure differential. For example, a flowing natural gas hydrate may include a flowing or flowable natural gas hydrate slurry **238**. In an embodiment, the flowing natural gas hydrate includes a natural gas hydrate and a carrier fluid. In an embodiment, the carrier fluid includes water or a flowable hydrocarbon. In an embodiment, the flowing natural gas hydrate includes a flowing clathrate or semi-clathrate composition with H_2O as a host molecule and a natural gas as a guest molecule. In an embodiment, the flowing natural gas hydrate includes a flowing natural gas hydrate slurry. In an embodiment, the flowing natural gas hydrate includes a flowing natural gas hydrate slush. In an embodiment, the flowing natural gas hydrate includes a pumpable natural gas hydrate.

FIG. **2**A illustrates an embodiment of the pipeline **130** wherein the cooling conduit **240** is located within the transportation conduit **220**, and the wall of the cooling conduit establishes a thermal coupling **242** with the flowing natural gas hydrate **234**. FIG. **2**B illustrates an embodiment where the cooling conduit abuts the transportation conduit, and the walls of the two conduits are thermally coupled **242** to form a heat transfer surface thermally coupled with the flowing natural gas hydrate. In an embodiment, the cooling conduit may run longitudinally with the transportation conduit, or may be wound around the transportation conduit (not illustrated) such as for example in a spiral. FIG. **2**C illustrates an embodiment of the pipeline wherein the cooling conduit and the transportation conduit are spaced apart, and are thermally coupled. In an embodiment of the pipeline, the cooling conduit and the transportation conduit are thermally coupled by a heat transfer structure **260**. For example, the heat transfer structure may include a heat plate or continuous heat pipes thermally coupling the heat-transfer fluid and the flowing natural gas hydrate. For example, the heat transfer structure may include a heat plate or continuous heat pipe that may be several feet, or hundreds of feet long, or more.

In an embodiment, the cooling conduit **240** and the transportation conduit **220** are thermally coupled by a highly thermally conductive material (not illustrated). For example, a highly thermally conductive material may include a material having $k>75$ W/(m·K) at 25° C. In an embodiment, the cooling conduit and the transportation conduit share a common thermally conductive wall portion (not illustrated)

In an embodiment, the heat-transfer fluid **250** includes a flowable solid-liquid phase slurry. In an embodiment, the heat-transfer fluid includes a flowable ice-water slurry. In an embodiment, the heat-transfer fluid includes a flowable hydrocarbon fluid. In an embodiment, the heat-transfer fluid includes water. In an embodiment, the water includes an anti-freeze agent. In an embodiment, the heat-transfer fluid and a carrier fluid of the natural gas hydrate are substantially the same material, e.g., water. In an embodiment, the heat-transfer fluid and a carrier fluid of the natural gas hydrate comprise a common material.

In an embodiment, the target temperature range includes a temperature range predicted to maintain a selected stability of the flowing natural gas hydrate **234** during a transit of a portion of the transportation conduit **220**. For example, a transit of a portion of the transportation conduit may include transit between the first geographic location **122** and the second geographic location **124**. In an embodiment, the target temperature range includes a temperature range predicted to maintain a decomposition rate of less than 10% of the flowing natural gas hydrate per 1000 km transit of the transportation conduit. In an embodiment, the target temperature range includes a temperature range predicted to maintain a decomposition rate of less than 5% of the flowing natural gas hydrate per 1000 km transit of the transportation conduit. In an embodiment, the target temperature range includes a temperature range predicted to maintain a decomposition rate of less than 1% of the flowing natural gas hydrate per 1000 km transit of the transportation conduit. In an embodiment, the target temperature range includes a temperature range predicted to maintain the flowing natural gas hydrate at least substantially within its hydrate stability range during transit of the portion of the transportation conduit. In an embodiment, the target temperature range includes a temperature range demonstrated to maintain a selected stability of the flowing natural gas hydrate during a transit of a portion of the transportation conduit. In an embodiment, the target temperature range includes a target temperature range (i) lower than the ambient temperature **192** surrounding the transportation conduit and (ii) predicted to maintain a selected stability of the flowing natural gas hydrate. Because the stable temperature range of the flowing natural gas hydrate is generally below the ambient temperature surrounding the transportation conduit, heat will leak from the environment into the flowing natural gas hydrate; the amount of this heat depending in a known fashion on the ambient temperature, the temperature of the flowing natural gas hydrate, and the thermal resistance between the environment and the inside of the transportation conduit. The role of the heat transfer fluid **250** and the cooling conduit **240** is to remove this leaked heat. The removal of heat into the heat transfer fluid occurs by virtue of maintaining the heat transfer fluid at a targeted temperature range below that at which the flowing natural gas hydrate is maintained at a selected stability, such that the heat leak from the transportation conduit into the cooling conduit (determined by their temperature difference and the thermal resistance between them) balances that from the ambient environment into the transportation conduit. The heat input into the heat transfer fluid can be dealt with by a number of methods. In an embodiment it will be actively dissipated into the environment by a heat pump or a refrigerator. In an embodiment it will be absorbed in sensible heat of the heat transfer fluid, leading to a temperature rise of the heat transfer fluid; since this process will become ineffective if the temperature of the heat transfer fluid rises above the thermal stability range of the natural gas hydrate, heat will be actively removed from the heat transfer fluid and dissipated into the environment by heat pumps or refrigerators spaced at locations along the pipeline. In an embodiment, the heat input into the heat transfer fluid is absorbed by a phase change of the heat transfer fluid (for instance melting of solid components of a solid liquid slurry, and/or vaporization of a liquid). This offers two advantages; the temperature of the heat transfer fluid remains constant during the process, and for a given amount of heat transfer fluid, the phase change process generally absorbs more heat than can be done by permissible temperature rises. The required temperature range of the heat transfer fluid can be determined by prediction, based on knowledge of the above parameters. The required temperature range of the heat transfer fluid can be determined empirically by monitoring (for example) the temperature of the flowing natural gas hydrate or of the heat transfer fluid and increasing cooling of the heat transfer fluid if the temperatures are too high relative to the stability range and reducing cooling if they are too low. During operation the amount of cooling required can vary due, for example, to changes in the ambient temperature, changes in the thermal resistance between the environment and the interior of the transportation conduit, or changes in the amount or temperature of the heat transfer fluid.

In an embodiment, the heat-transfer fluid **250** is selected to absorb heat from the flowing natural gas hydrate **234** by undergoing a phase change. For example, the phase change may include melting ice or an ice slurry to water; this can be advantageous since the melting point of ice is generally less than the decomposition temperature of gas hydrates. For example, the phase change may include water contained at a selected low vapor pressure (chosen such that the resultant vaporization temperature is less than a stable temperature of the natural gas hydrate), and evaporating or boiling the water absorbs heat from the flowing natural gas hydrate. In an embodiment, both types of phase changes, melting and vaporization can be utilized. In an embodiment, in an open-cycle system, the water vapor produced by the boiling is discarded by venting or pumping out of the cooling conduit. In an embodiment, in closed-cycle system, the water vapor produced by the boiling is condensed and recycled. In an embodiment, the heat-transfer fluid is maintained at a vapor pressure of less than 1 bar and is selected to achieve a specified T_{VAP} configured to cool the heat-transfer fluid to the target temperature range. In an embodiment, the heat-transfer fluid is selected to absorb heat from the flowing natural gas hydrate by undergoing a phase change from ice-in-an-ice-water slurry to water-in-the-ice-water slurry. In an embodiment, the water-in-the-ice-water slurry may be discarded by pumping out of the cooling conduit in an open-cycle version.

In an embodiment, the pipeline system **110** includes an exhaust system **114** configured to vent a portion of the heat-transfer fluid **250** after the heat-transfer fluid has undergone the phase change. In embodiments where the heat transfer fluid is maintained at a sub-ambient pressure, the exhaust system can comprise a pump in order to raise the pressure of the exhausted gas. In an embodiment, the heat-transfer fluid flows from the first geographical location **122** to the second geographical location **124**. In an embodiment, the heat-transfer fluid flows from the second geographical location to the first geographical location.

In an embodiment, the pipeline system **110** includes a return-conduit running between the second geographical location **124** and the first geographical location **122**. In embodiments where the heat transfer fluid flows from the first geographical location **122** to the second geographical location **124**, the return-conduit contains a portion of the heat-transfer fluid **250** withdrawn from the cooling conduit **240** at the second geographical location. The withdrawn heat-transfer fluid is flowing from the second geographical location toward the first geographical location. In other embodiments where the heat transfer fluid flows from the second geographical location **124** to the first geographical location **122**, heat transfer fluid is withdrawn at the first geographical location and returns it to the second geographical location. These embodiments are not illustrated in FIG. **2**. However, FIG. **11** illustrates an embodiment that includes a recovered-liquid conduit **1050** returning a recovered liquid **1060** from the second geographical location toward the first geographical location. The return conduit may or may not be thermally coupled to the flowing natural gas hydrate **234**, correspondingly the returning heat transfer fluid may or may not take part in cooling the flowing natural gas hydrate.

FIG. **3** illustrates an alternative embodiment **200** of the pipeline system **110** and the pipeline **130** illustrated in FIGS. **1-2**. FIG. **3** illustrates a longitudinal section view B-B of the segment **132** illustrated in FIG. **2**. In this alternative embodiment, the pipeline system further includes a cooling system **260** configured to cool the heat-transfer fluid **250** to the target temperature range. In an embodiment, the cooling system includes an open-cycle cooling system configured to cool the heat-transfer fluid to the target temperature range. In an embodiment, the cooling system includes a closed-cycle refrigeration system configured to cool the heat-transfer fluid to the target temperature range. For example, the closed-cycle refrigeration system may include a single phase, or a phase change based system. In an embodiment, the closed-cycle refrigeration system further includes a closed-cycle refrigeration system configured to cool the heat-transfer fluid to the target temperature range using multiple phase changes. For example, multiple phase changes may include a phase change from a solid to a liquid, and then a phase change from liquid to a gas. For example, the heat-transfer fluid **250** of FIG. **2**A may pass through three phases. In an embodiment, the closed-cycle refrigeration system further includes a refrigeration controller (not illustrated) coupled with the closed-cycle refrigeration system and configured to regulate cooling of the heat-transfer fluid by the closed-cycle refrigeration system to achieve the target temperature range of the heat-transfer fluid.

In an embodiment, the closed-cycle cooling system includes an evaporator portion **262** located at a site along the cooling conduit **240** and having a direct or an indirect thermal contact with the heat-transfer fluid **250**. In an embodiment, the closed-cycle cooling system includes evaporator portions respective located at a plurality of sites along the cooling conduit, each of the plurality of sites having a direct or an indirect thermal contact with the heat-transfer fluid. In an embodiment, the cooling system is powered at least in part by combustion of natural gas released by decomposition of the flowing natural gas hydrate **234** contained in the transportation conduit. For example, the cooling system may be implemented using absorption refrigeration, or the cooling system may be implemented using electrical power generated by combustion of the released natural gas. In an embodiment, the closed-cycle cooling system includes a condenser portion **264**.

FIG. **4** illustrates an alternative embodiment **300** of the pipeline system **110** and the pipeline **130** illustrated in FIGS. **1-2**. FIG. **4** illustrates a longitudinal section view B-B of the segment **132** of the pipeline illustrated in FIG. **2**. In this alternative embodiment, the pipeline system further includes a removal system **370** withdrawing at least a portion of the heat-transfer fluid **250** from the cooling conduit **240**. The pipeline system further includes an injection system **380** introducing the withdrawn heat-transfer fluid into the cooling conduit after cooling of the withdrawn heat-transfer fluid by the cooling system **260**. The injection system **380** may be configured to reintroduce the withdrawn heat transfer fluid into the cooling conduit at a location either downstream, upstream, or proximal to the withdrawal location.

Returning to the environment **200** illustrated in part by FIG. **2**, in an embodiment, the pipeline system of **110** includes a hydrate pump **116** urging the flowing natural gas hydrate **234** toward the second geographic location **124**. In an embodiment, the hydrate pump includes a pressure controller **118** configured to regulate the pressure of the contained natural gas hydrate flowing between the first geographic location **122** and the second geographic location. The regulated pressure and the target temperature range are predicted to maintain the selected stability of the natural gas hydrate flowing from the first geographic location to the second geographic location. In an embodiment, at least a portion of the cooling conduit **240** has a slope providing a gravitational flow of the heat-transfer fluid **250** either from the first geographical location toward the second geographical location, or from the second geographic location toward the first geographical location. In an embodiment, at least a portion of the cooling conduit includes a capillary member (not illustrated) configured to provide the flow of the heat-transfer fluid either from the first geographical location toward the second geographical location, or from the second geographical location toward the first geographical location. In an embodiment, the pipeline system includes a fluid pump **117** urging the flowing of the heat-transfer fluid from the first geographical location toward the second geographical location, or from the second geographical location toward the first geographical location. In an embodiment, the pipeline system includes an insulating material (not illustrated) thermally separating the transportation conduit from the ambient temperature **192** of the environment **100** surrounding the transportation conduit. For example, the insulating material may include earthen material burying the transportation conduit, or insulation thermally separating the transportation conduit from the environment, such as foam, aerogel, or multi-layer insulation. In an embodiment, the pipeline system includes a temperature sensor **121** responsive to a temperature of the natural gas hydrate. In an embodiment, the pipeline system includes a temperature sensor responsive to a temperature of the heat-transfer fluid. In an embodiment, the pipeline system includes a pressure sensor **119** responsive to a pressure of the natural gas hydrate.

FIGS. **2-4** illustrate an alternative embodiment of the pipeline system **110**. In this alternative embodiment, the pipeline system includes the transportation conduit **220** configured to contain the natural gas hydrate **234** flowing **112** from the first geographic location **122** to the second geographic location **124**. The pipeline system includes the cooling conduit **240** running parallel to the transportation conduit, having a heat-transfer surface **242** thermally coupled with the natural gas hydrate contained within the transportation conduit, and configured to contain the heat-transfer fluid **250** flowing between the first geographic location and the second geographic location. The pipeline system includes the cooling system **260** configured to cool the heat-transfer fluid to a target temperature range predicted to maintain a selected stability of the natural gas hydrate contained by and flowing through the transportation conduit. In an embodiment, the pipeline system includes the removal system **370** configured to withdraw at least a portion of the heat-transfer fluid from the cooling conduit. The pipeline system also includes the injection system **380** configured to introduce the withdrawn heat-transfer fluid into the cooling conduit after cooling of the withdrawn heat-transfer fluid by the cooling system **260**. In an embodiment, the pipeline system includes the hydrate pump (not illustrated) configured to urge the flow of the natural gas hydrate toward the second geographic location. In an embodiment, the pipeline system includes a fluid pump (not illustrated) configured to urge the flow of the heat-transfer fluid toward the second geographical location, or toward the first geographical location.

FIGS. **2-4** illustrate another alternative embodiment of the pipeline system **110**. In this alternative embodiment, the pipeline system includes the transportation conduit **220** configured to contain a gas clathrate **230** flowing **112** from the first geographical location **122** to the second geographical location **124**. The pipeline system includes the cooling conduit **240** running parallel to the transportation conduit, having a heat-transfer surface **242** thermally coupled with the flowing gas clathrate, and containing the flowing heat-transfer fluid **250**. The flowing heat-transfer fluid has a target temperature range predicted to maintain a selected stability of the gas clathrate flowing from the first geographical location to the second geographical location. In an embodiment, the gas clathrate includes the gas hydrate **232**. In an embodiment, the gas hydrate includes the natural gas hydrate **234**. In an embodiment, the gas hydrate includes a CO_2 hydrate **236**. For example, the CO_2 hydrate may be bound for sequestration.

In an embodiment of the another alternative embodiment, the pipeline system **110** includes the cooling system **260** configured to cool the heat-transfer fluid to the target temperature range. In an embodiment, the pipeline system includes a pump system (not illustrated) configured to urge the flowing gas clathrate from the first geographical location to the second geographical location. In an embodiment, the pipeline system includes a pump system (not illustrated) configured to urge the flowing heat-transfer fluid from the first geographical location toward the second geographical location, or from the second geographical location toward the first geographical location.

FIGS. **2-4** illustrate a further alternative embodiment of the pipeline system **110**. In this further alternative embodiment, the pipeline system includes the transportation conduit **220** configured to contain the gas clathrate **230** flowing from the first geographic location **122** to the second geographic location **124**. The pipeline system includes the cooling conduit **240** running parallel to the transportation conduit, having a heat-transfer surface **242** thermally coupled with gas clathrate contained within the transportation conduit, and configured to contain a heat-transfer fluid flowing between the first geographic location and the second geographic location. The pipeline system includes the cooling system **260** configured to cool the heat-transfer fluid to a target temperature range predicted to maintain a selected stability of the gas clathrate contained by and flowing through the transportation conduit. In an embodiment, the gas clathrate includes a gas hydrate **232**. In an embodiment, the gas hydrate includes the natural gas hydrate **234**. In an embodiment, the gas hydrate includes a CO_2 hydrate **236**.

In an embodiment of this further alternative embodiment, the pipeline system **110** includes the cooling system **260** configured to cool the heat-transfer fluid **250** to the target temperature range. In an embodiment, the pipeline system includes a pump system (not illustrated) configured to urge the flowing gas clathrate from the first geographical location **122** to the second geographical location **124**. In an embodiment, the pipeline system includes a pump system (not illustrated) configured to urge the flowing heat-transfer fluid from the first geographical location toward the second geographical location, or from the second geographical location toward the first geographical location.

FIGS. **2-4** illustrate another alternative embodiment of the pipeline system **110**. In this alternative embodiment, the pipeline system includes the transportation conduit **220** configured to contain a gas clathrate **230** flowing from the first geographic location **122** to the second geographic location **124**. The pipeline system includes the cooling conduit **240** running parallel to the transportation conduit, having a heat-transfer surface **242** thermally coupled with gas clathrate contained within the transportation conduit, and configured to contain a heat-transfer fluid flowing between the first geographic location and the second geographic location. The pipeline system includes a cooling system configured to cool the heat-transfer fluid to a target temperature range predicted to maintain a selected stability of gas clathrate contained by and flowing through the transportation conduit.

In an embodiment of this another alternative embodiment, the gas clathrate **230** includes a gas hydrate **232**. In an embodiment, the gas hydrate includes the natural gas hydrate **234**. In an embodiment, the gas hydrate includes a CO_2 hydrate **236**.

FIG. **5** illustrates an example operational flow **400** implemented in a pipeline system. After a start operation, the operational flow includes a fluid transport **410** operation. The fluid transport operation includes flowing a gas clathrate from a first geographic location to a second geographic location through a transportation conduit of the pipeline system. In an embodiment, the fluid transport operation may be implemented in part or in whole using the transportation conduit **220** described in conjunction with FIG. **2**. A clathrate stability control operation **420** includes flowing a heat-transfer fluid between the first geographic location and the second geographic location through a cooling conduit of the pipeline system. The cooling conduit running parallel to the transportation conduit and having a heat-transfer surface thermally coupled with the flowing gas clathrate. The flowing heat-transfer fluid has a target temperature range predicted to maintain a selected stability of the flowing gas clathrate. In an embodiment, the clathrate stability control operation may be implemented in part or in whole using the cooling conduit **240** described in conjunction with FIG. **2**. The operational flow includes an end operation. In an embodiment, the gas clathrate includes a gas hydrate **232**. In an embodiment, the gas hydrate includes the natural gas hydrate **234**. In an embodiment, the gas hydrate includes a CO_2 hydrate **236**.

FIG. **6** illustrates an example embodiment of a pipeline system **510**. The pipeline system includes a transportation conduit **520** containing the gas hydrate **232** flowing from the first geographical location **122** to the second geographical location **124**. The pipeline system includes a cooling system **560** in thermal contact with the flowing gas hydrate and maintaining the temperature of the flowing gas hydrate within a target temperature range predicted to maintain a selected stability of the flowing gas hydrate. In an embodiment, the gas hydrate **232** includes a natural gas hydrate **234**. In an embodiment, the gas hydrate includes the CO_2 gas hydrate **236**. In an embodiment, the gas hydrate includes a CO_2 gas hydrate and a natural gas hydrate.

In an embodiment, the transportation conduit **520** contains the flowing gas hydrate **232** at a low pressure. In an embodiment, the transportation conduit contains the flowing gas hydrate at a pressure less than about 50 bars. In an embodiment, the transportation conduit contains the flowing gas hydrate at a pressure less than about 20 bars. In an embodiment, the transportation conduit contains the flowing gas hydrate at a pressure less than about 10 bars. In an embodiment, the transportation conduit contains the flowing gas hydrate at a pressure less than about 5 bars.

In an embodiment, the transportation conduit **520** includes a metal or plastic material. In an embodiment, the cooling system **560** includes an evaporator portion **562** in thermal contact with the flowing gas hydrate **232**. In an embodiment, the evaporator portion is located within the transportation conduit and in direct thermal contact the flowing gas hydrate, e.g., separated only by a heat transfer surface of the evaporator portion. In an embodiment, the evaporator portion has an indirect thermal contact the flowing gas hydrate (not illustrated); for example they may be thermally coupled by a conductive member, by a heat pipe, by a second coolant loop, etc. In an embodiment, at least a portion of a wall of the transportation conduit is disposed between the flowing gas hydrate and the evaporator portion of the cooling system (not illustrated). In an embodiment, the at least a portion of the wall of the transportation conduit has a thermally conductivity of k>30 W/(m·K). For example, carbon steel has a thermal conductivity k of 54 at 25° C., and pure aluminum has a thermal conductivity k of 250 at 25° C. In an embodiment, the at least a portion of the wall of the transportation conduit has a thermally conductivity of k>70 W/(m·K).

In an embodiment, the evaporator portion **562** of the cooling system **560** is positioned at a potential hot spot of the transportation conduit **520**. In an embodiment, the cooling system includes at least two cooling systems. In an embodiment, the at least two cooling systems are spaced-apart along a length of the transportation conduit. In an embodiment, the cooling system includes a condenser **566**.

In an embodiment, the cooling system **560** includes an open loop cooling system. In an embodiment, the cooling system includes a closed-cycle cooling system. In an embodiment, the closed-cycle cooling system includes a refrigeration system **564**. In an embodiment, the refrigeration system is powered by combustion of natural gas released by decomposition of the flowing natural gas hydrate. In an embodiment, the decomposition of the flowing natural gas hydrate occurs in a normal course of transportation through the transportation conduit. In an embodiment, the decomposition of the flowing natural gas hydrate occurring by an intentional withdrawal and decomposition from the flowing natural gas hydrate. In an embodiment, the closed-cycle cooling system includes a passive closed-cycle cooling system. For example, a passive closed-cycle cooling system may include a heat pipe or a heat plate. In an embodiment, the passive closed-cycle cooling system includes a single phase closed-cycle cooling system. In an embodiment, the passive closed-cycle cooling system includes a two phase closed-cycle cooling system.

In an embodiment, the pipeline system **510** includes a pump system (not illustrated) urging the flowing gas hydrate **234** through at least the portion of the transportation conduit. In an embodiment, the pump system is powered by combustion of natural gas decomposed from the flowing natural gas hydrate transported in the transportation conduit. See decomposition unit **570**. In an embodiment, the pipeline system includes a pressure sensor (not shown) responsive to a pressure of the flowing gas hydrate or of the heat transfer fluid. In an embodiment, the pipeline system includes a temperature sensor (not shown) responsive to a temperature of the flowing gas hydrate, and/or a temperature of the heat transfer fluid. In an embodiment, the pipeline system includes a controller **580** configured to control a pressure or temperature of the flowing gas hydrate in response to a sensed pressure or temperature of the flowing gas hydrate or of the heat transfer fluid.

FIG. **6** illustrates an alternative embodiment of the pipeline system **510**. In the alternative embodiment, the pipeline system includes a transportation conduit **520** configured to contain the natural gas hydrate **234** flowing from the first geographic location **122** to the second geographic location **124**. The pipeline system includes the cooling system **560** configured to cool the contained and flowing natural gas hydrate to a target temperature range predicted to maintain a selected stability of the flowing natural gas hydrate. In an embodiment, the cooling system is configured to be powered by combustion of natural gas released by decomposition of the contained flowing natural gas hydrate through the transportation conduit.

In an embodiment of this alternative embodiment, the pipeline system **510** includes a cooling system controller **568** coupled with the cooling system **560** and configured to regulate cooling of the flowable natural gas hydrate **234** by the cooling system. In an embodiment, the cooling system controller is configured to regulate cooling by the cooling system to achieve a target temperature range of the flowable natural gas hydrate predicted to maintain a selected stability of the flowable natural gas hydrate. In an embodiment, the target temperature range includes a target temperature range of the flowable natural gas hydrate (i) lower than the ambient temperature **192** surrounding the transportation conduit and (ii) predicted to maintain a selected stability of the flowing natural gas hydrate. Because the stable temperature range of the flowing natural gas hydrate is generally below the ambient temperature surrounding the transportation conduit, heat will leak from the environment into the flowing natural gas hydrate; the amount of this heat depending in a known fashion on the ambient temperature, the temperature of the flowing natural gas hydrate, and the thermal resistance between the environment and the inside of the transportation conduit. The role of the cooling system is to remove this leaked heat. The amount of cooling required can be determined by prediction, based on knowledge of the above parameters. The amount of cooling required can be determined empirically by monitoring (for example) the temperature of the flowing natural gas hydrate and increasing cooling if it is too high relative to the target temperature range and reducing cooling if it is too low. During operation the amount of cooling required can vary due, for example, to changes in the ambient temperature, or changes in the thermal resistance between the environment and the interior of the transportation conduit. In an embodiment, the target temperature range is responsive to the stability temperature and pressure range profile of the particular natural gas hydrate being transported in the transportation conduit. For example, the stability temperature and pressure range profile for a particular natural gas hydrate may be about 15 degrees C. at one atmospheric pressure. For example, the stability temperature and pressure range profile for a particular natural gas hydrate may also be a function of its particular chemical additives. In an embodiment, the cooling system controller is configured to regulate cooling by the cooling system of the flowable natural gas hydrate during transport of the flowable natural gas hydrate through a portion of the transportation conduit.

In an embodiment of this alternative embodiment, the pipeline system **510** includes a pressure controller **580** configured to regulate pressure of the flowable natural gas hydrate **234** contained within the portion of the transportation conduit **520**. In an embodiment, the pipeline system includes an insulating material (not illustrated) thermally separating the transportation conduit from the ambient temperature **192** surrounding the transportation conduit of the pipeline system. In an embodiment, the pipeline system includes a pumping system (not illustrated) configured to urge the flowable natural gas hydrate through at least the portion of the transportation conduit. In an embodiment, the pipeline system includes a pumping system (not illustrated) configured to be powered by combustion of natural gas decomposed from the flowing natural gas hydrate being transported in the transportation conduit. In an embodiment, the pipeline system includes a pressure sensor (not illustrated) responsive to a pressure of the flowable gas hydrate.

In an embodiment, the pipeline system includes a temperature sensor (not illustrated) responsive to a temperature of the flowable gas hydrate.

FIG. **7** illustrates an example operational flow **600** implemented in a pipeline transportation system. After a start operation, the operational flow includes a fluid transport operation **610**. The fluid transport operation includes flowing a natural gas hydrate from a first geographical location to another geographical location through a transportation conduit of the pipeline system. In an embodiment, the fluid transport operation may be implemented in part or in whole using the transportation conduit **520** described in conjunction with FIG. **6**. A hydrate stability control operation **620** includes withdrawing sufficient heat from the flowing natural gas hydrate to maintain the flowing natural gas hydrate within a target temperature range predicted to maintain a selected stability of the flowing natural gas hydrate. In an embodiment, the hydrate stability control operation may be implemented in part or in whole using the cooling system **560** described in conjunction with FIG. **6**. The operational flow includes an end operation.

In an embodiment, the hydrate stability control operation **620** may include at least one additional operation, such as an operation **622**, an operation **624**, or an operation **626**. The operation **622** includes withdrawing sufficient heat from the flowing natural gas hydrate using an evaporator immersed in the flowing natural gas hydrate. The operation **624** includes withdrawing sufficient heat from the flowing natural gas hydrate using a passive cooling system. The operation **626** includes withdrawing sufficient heat from the flowing natural gas hydrate using an active cooling system. In an embodiment, the operational flow **600** may include at least one additional operation, such as an operation **630**. The operation **630** includes controlling the withdrawing of sufficient heat at least partially based on a sensed temperature of the flowing natural gas hydrate.

FIG. **8** illustrates an example operational flow **700** implemented in a pipeline transportation system. After a start operation, the operational flow includes a temperature controlled hydrate flow operation **710**. The temperature controlled hydrate flow operation includes maintaining a flowable natural gas hydrate within a target temperature range during its transit of a portion of the pipeline system using refrigeration powered by combustion of natural gas decomposed from the flowable natural gas hydrate transiting the portion of the pipeline system. The target temperature range is predicted to provide a selected stability of the flowable natural gas during its transit of the portion of the pipeline system. In an embodiment, the temperature controlled hydrate flow operation may be implemented in part or in whole using the pipeline system **510** described in conjunction with FIG. **6**. The operational flow includes an end operation.

In an embodiment, the refrigeration is powered at least in part by combustion of natural gas released by decomposition of the flowable natural gas hydrate occurring in the normal course of transiting the portion of the pipeline system. In an embodiment, the refrigeration is powered at least in part by combustion of natural gas intentionally withdrawn and decomposed from the natural gas hydrate transiting the portion of the pipeline system. In an embodiment, the target temperature range provides a selected flowability of the natural gas hydrate. The target temperature range is selected at least partially based on the stability temperature and pressure phase relationship of the particular natural gas hydrate transiting the portion of the pipeline system. In an embodiment, the target temperature range is effective to maintain a selected stability of the flowing natural gas hydrate during its transit of a portion of the pipeline system.

FIG. **9** illustrates an example embodiment of a pipeline system **810** that transports flowable natural gas hydrate slurries. The pipeline system includes a transportation conduit **820** configured to contain a natural gas hydrate slurry **238** flowing **112** from a first geographic location to a second geographic location, such as the first geographic location **122** and the second geographic location **124** illustrated in FIG. **1**. The natural gas hydrate slurry includes a natural gas hydrate and a liquid. The pipeline system includes a removal system **870** configured to withdraw a portion of the liquid from the flowing natural gas hydrate slurry. The pipeline system includes a cooling system **860** configured to cool the withdrawn liquid to a target temperature range. The target temperature range is predicted to provide a selected stability of the natural gas slurry during transit of the natural gas slurry over at least a portion of the distance from the first geographic location to the second geographic location. The pipeline includes a mixing system **880** configured to reintroduce the cooled withdrawn liquid into the flowing natural gas slurry.

In an embodiment, the removal system **870** is located between the first geographical location **122** and the second geographical location **124**. In an embodiment, the removal system is configured to separate and withdraw the liquid from the flowing natural gas hydrate slurry. In an embodiment, the cooling system **860** includes an open-cycle cooling system or a closed-cycle cooling system. In an embodiment, the cooling system includes an evaporator (not illustrated). In an embodiment, the cooling system includes a condenser **864**. In an embodiment, the cooling system includes a controller **868** coupled with the cooling system and regulating cooling of the withdrawn liquid by the cooling system to achieve the target temperature range. In an embodiment, the cooling system is powered by combustion of natural gas decomposed from the flowing natural gas hydrate slurry. In an embodiment, the removal system **870** or the mixing system **880** is powered by combustion of natural gas decomposed from the natural gas hydrate slurry. In an embodiment, the mixing system is configured to reintroduce and mix the cooled withdrawn liquid into the flowing natural gas hydrate slurry.

FIG. **10** illustrates an example operational flow **900** implemented in a pipeline system that transports flowable natural gas hydrate slurries from a first geographical location to the second geographical location. After a start operation, the operational flow includes a fluid transport operation **910**. The fluid transport operation includes flowing a natural gas hydrate slurry through a transportation conduit of the pipeline system. The natural gas hydrate slurry including a natural gas hydrate and a liquid. In an embodiment, the fluid transport operation may be implemented in part or in whole using the transportation conduit **820** described in conjunction with FIG. **9**. An extraction operation **920** includes withdrawing a portion of the liquid from the flowing natural gas hydrate slurry. In an embodiment, the extraction operation may be implemented in part or in whole using the removal system **870** described in conjunction with FIG. **9**. A chilling operation **930** includes cooling the withdrawn liquid to a target temperature range predicted to provide a selected stability of the natural gas slurry during transit of the natural gas slurry from the first geographic location to the second geographic location. In an embodiment, the chilling operation may be implemented in part or in whole using the cooling system **860** described in conjunction with FIG. **9**. An additive operation **940** includes introducing the cooled withdrawn liquid into the flowing natural gas slurry. In an embodiment, the additive operation may be implemented in part or in whole using the mixing system **880** described in conjunction with FIG. **9**. The operational flow includes an end operation.

In an embodiment, the operational flow **900** may include at least one additional operation, such as an operation **950**. The operation **950** includes powering the cooling of the withdrawn liquid by combustion of natural gas decomposed from the flowing natural gas hydrate slurry.

FIG. **11** illustrates an example pipeline system **1010**. The pipeline system **1010** includes the pipeline **1013**, and illustrates an alternative embodiment of the segment **132** running between the first geographic location **122** and the second geographic location **124**. The pipeline includes a transportation conduit **1020** configured to contain and flow **112** natural gas hydrate slurry **1030** from the first geographical location **122** to the second geographical location **124**. The pipeline system includes a decomposition system **1090** located at the second geographical location and configured to decompose at least a portion of the flowed natural gas hydrate slurry. For example, the decomposition system may be associated with a facility removing natural gas from the hydrate slurry and transmitting removed natural gas to residential and commercial users for consumption. For example, flow arrow **1092** illustrates the decomposition unit receiving natural gas hydrate slurry from the transportation conduit **1020**. The pipeline system includes a reclamation system **1070** located at the second geographical location and configured to recover at least a portion of a liquid component released from the decomposed natural gas hydrate slurry. For example, flow arrow **1072** illustrates the reclamation system recovering at least a portion of a liquid component released from the decomposed natural gas hydrate slurry. For example, flow arrow **1074** illustrates the reclamation system introducing the recovered liquid component **1060** into the recovered-liquid conduit. The pipeline includes a recovered-liquid conduit **1050** configured to contain and flow **1014** the recovered liquid component **1060** from the second geographical location toward the first geographical location. The pipeline system includes a combiner system **1080** configured to introduce the recovered liquid component into natural gas hydrate slurry subsequently flowing through the transportation conduit toward the second geographical location from the first geographical location. For example, flow arrow **1084** illustrates the combiner system introducing the recovered liquid component into natural gas hydrate slurry subsequently flowing through the transportation conduit.

In an embodiment, the reclamation system **1070** is configured to separate and recover at least a portion of a liquid component from the decomposed natural gas hydrate slurry. In an embodiment, the reclamation system is configured to recover at least a portion of a liquid component from the flowing natural gas hydrate slurry and recover a liquid product released by decomposition of the natural gas hydrate slurry. In an embodiment, the combiner system **1080** is further configured to receive the recovered liquid component **1060** from the recovered-liquid conduit. For example, arrow **1082** illustrates the combiner system receiving at least a portion of the recovered liquid component from the recovered-liquid conduit. In an embodiment, the combiner system is located at the first geographical location **122**. In an embodiment, the combiner system is located at point (not illustrated) between the first geographical location **122** and the second geographical location **124**. In an embodiment, the combiner system is located at point (not illustrated) upstream of the flow **112** from the first geographical location. In an embodiment, the pipeline system includes an injection system (not illustrated) configured to introduce the recovered liquid (illustrated by flow arrow **1074**) into t recovered-liquid conduit. In an embodiment (not illustrated) at least a portion of the liquid portion of the natural gas hydrate slurry is recovered at location **124** and returned through a second recovered liquid conduit to location **122**, where it may be combined with natural gas hydrate to form natural gas hydrate slurry thereupon sent via the transportation conduit **1020** from location **122** to location **124**. In an embodiment, both the liquid product released by decomposition of the natural gas hydrate and the liquid portion of the natural gas hydrate slurry are returned from location **124** to location **122** in separate recovered liquid conduits. In another embodiment, both these liquids are substantially the same composition (e.g., water), and are returned in the same conduit, i.e., the recovered liquid conduit and the second recovered liquid conduit are the same. In another embodiment, the recovered liquid is used as the heat transfer fluid, in which case the recovered liquid conduit **1060** functions as the cooling conduit **240**.

FIG. **12** illustrates an example operational flow **1100** implemented in a pipeline system that transports flowable natural gas hydrate slurries from a first geographic location to a second geographic location, such as the first geographical location **122** to the second geographical location **124**. After a start operation, the operation flow includes a fluid transport operation **1110**. The fluid transport operation includes flowing natural gas hydrate slurry through a transportation conduit of the pipeline system from a first geographical location to the second geographical location. In an embodiment, the fluid transport operation may be implemented in part or in whole using the transportation conduit **1020** described in conjunction with FIG. **11**. A separation operation **1120** includes decomposing at least a portion of the flowed natural gas hydrate slurry at the second geographical location. In an embodiment, the separation operation may be implemented in part or in whole using the decomposition system **1090** described in conjunction with FIG. **11**. A reclamation operation **1130** includes recovering at least a portion of a liquid component released from the decomposed natural gas hydrate slurry. In an embodiment, the reclamation operation may be implemented in part or in whole using the reclamation system **1070** described in conjunction with FIG. **11**. A recovered liquid transportation operation **1140** includes flowing the recovered liquid component from the second geographical location toward the first geographical location through a recovered-liquid conduit of the pipeline system. In an embodiment, the recovered liquid transportation may be implemented in part or in whole using the recovered-liquid conduit **1050** described in conjunction with FIG. **11**. A mixing operation **1150** includes introducing the recovered liquid component into natural gas hydrate slurry subsequently flowing through the transportation conduit toward the second geographical location from the first geographical location. In an embodiment, the mixing operation may be implemented in part or in whole using the combiner system **1080** described in conjunction with FIG. **11**. The operational flow includes an end operation.

In an embodiment, the operational flow **1100** includes absorbing heat from natural gas hydrate slurry flowing through the transportation conduit using the recovered liquid component flowing through the recovered-liquid conduit. In an embodiment, the operational flow includes chilling the recovered liquid component and forming an ice/liquid slurry recovered liquid component. In an embodiment, the operational flow includes reducing the pressure of the recovered liquid component flowing through the recovered-liquid conduit to achieve a target boiling point of the recovered liquid component selected to absorb heat from the flowing natural gas hydrate by undergoing a phase change. For example, the pressure of a recovered liquid component may be reduced to selected low vapor pressure such that the recovered liquid component evaporates or boils as it absorbs heat from the flowing natural gas hydrate slurry. For example, evaporated water from the recovered liquid component may be discarded by pumping out of the recovered-liquid conduit. For example, evaporated water from the recovered liquid component may be condensed and recycled in a closed-cycle system.

All references cited herein are hereby incorporated by reference in their entirety or to the extent their subject matter is not otherwise inconsistent herewith.

In some embodiments, "configured" includes at least one of designed, set up, shaped, implemented, constructed, or adapted for at least one of a particular purpose, application, or function.

It will be understood that, in general, terms used herein, and especially in the appended claims, are generally intended as "open" terms. For example, the term "including" should be interpreted as "including but not limited to." For example, the term "having" should be interpreted as "having at least." For example, the term "has" should be interpreted as "having at least." For example, the term "includes" should be interpreted as "includes but is not limited to," etc. It will be further understood that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of introductory phrases such as "at least one" or "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a receiver" should typically be interpreted to mean "at least one receiver"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, it will be recognized that such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of "at least two chambers," or "a plurality of chambers," without other modifiers, typically means at least two chambers).

In those instances where a phrase such as "at least one of A, B, and C," "at least one of A, B, or C," or "an [item] selected from the group consisting of A, B, and C," is used, in general such a construction is intended to be disjunctive (e.g., any of these phrases would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, or A, B, and C together, and may further include more than one of A, B, or C, such as A_1, A_2, and C together, A, B_1, B_2, C_1, and C_2 together, or B_1 and B_2 together). It will be further understood that virtually any disjunctive word or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B."

The herein described aspects depict different components contained within, or connected with, different other components. It is to be understood that such depicted architectures are merely examples, and that in fact many other architectures can be implemented which achieve the same functionality. In a conceptual sense, any arrangement of components to achieve the same functionality is effectively "associated" such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality can be seen as "associated with" each other such that the desired functionality is achieved, irrespective of architectures or intermedial components. Likewise, any two components so associated can also be viewed as being "operably connected," or "operably coupled," to each other to achieve the desired functionality. Any two components capable of being so associated can also be viewed as being "operably couplable" to each other to achieve the desired functionality. Specific examples of operably couplable include but are not limited to physically mateable or physically interacting components or wirelessly interactable or wirelessly interacting components.

With respect to the appended claims, the recited operations therein may generally be performed in any order. Also, although various operational flows are presented in a sequence(s), it should be understood that the various operations may be performed in other orders than those which are illustrated, or may be performed concurrently. Examples of such alternate orderings may include overlapping, interleaved, interrupted, reordered, incremental, preparatory, supplemental, simultaneous, reverse, or other variant orderings, unless context dictates otherwise. Use of "Start," "End," "Stop," or the like blocks in the block diagrams is not intended to indicate a limitation on the beginning or end of any operations or functions in the diagram. Such flowcharts or diagrams may be incorporated into other flowcharts or diagrams where additional functions are performed before or after the functions shown in the diagrams of this application. Furthermore, terms like "responsive to," "related to," or other past-tense adjectives are generally not intended to exclude such variants, unless context dictates otherwise.

While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed is:

1. A pipeline system comprising:

a transportation conduit containing a gas hydrate flowing from a first geographical location to another geographical location; and

a cooling system including a cooling conduit, the transportation conduit being disposed exterior to the cooling conduit, the cooling system being in thermal contact with the flowing gas hydrate and maintaining the temperature of the flowing gas hydrate within a target temperature range predicted to maintain a selected stability of the flowing gas hydrate, the cooling system including a closed-cycle cooling system that includes a refrigeration system powered by combustion of gas released by decomposition of the flowing gas hydrate.

2. The pipeline system of claim **1**, wherein the gas hydrate includes a natural gas hydrate.

3. The pipeline system of claim **1**, wherein the gas hydrate includes a CO_2 gas hydrate.

4. The pipeline system of claim **1**, wherein the transportation conduit contains the flowing gas hydrate at a low pressure.

5. The pipeline system of claim **1**, wherein the transportation conduit contains the flowing gas hydrate at a pressure less than 20 bars.

6. The pipeline system of claim **1**, wherein the transportation conduit contains the flowing gas hydrate at a pressure less than 5 bars.

7. The pipeline system of claim **1**, wherein the transportation conduit includes a metal or plastic material.

8. The pipeline system of claim **1**, wherein the cooling system includes an evaporator portion composing a portion of the cooling conduit in thermal contact with the flowing gas hydrate.

9. The pipeline system of claim **8**, wherein the evaporator portion is located within the transportation conduit and in direct thermal contact with the flowing gas hydrate.

10. The pipeline system of claim **8**, wherein the evaporator portion has an indirect thermal contact with the flowing gas hydrate.

11. The pipeline system of claim **1**, wherein at least a portion of a wall of the transportation conduit is disposed between the flowing gas hydrate and an evaporator portion composing a portion of the cooling conduit of the cooling system.

12. The pipeline system of claim **11**, wherein at least the portion of the wall of the transportation conduit has a thermal conductivity of $k>30$ W/(m*K).

13. The pipeline system of claim **11**, wherein at least the portion of the wall of the transportation conduit has a thermal conductivity of $k>70$ W/(m*K).

14. The pipeline system of claim **1**, wherein an evaporator portion composing a portion of the cooling conduit of the cooling system is positioned at a potential hot spot of the transportation conduit.

15. The pipeline system of claim **1**, further comprising:
a pump system urging the flowing gas hydrate through at least a portion of the transportation conduit.

16. The pipeline system of claim **15**, wherein the pump system is powered by combustion of gas decomposed from the flowing gas hydrate transported in the transportation conduit.

17. The pipeline system of claim **1**, further comprising:
a pressure sensor responsive to a pressure of the flowing gas hydrate.

18. The pipeline system of claim **1**, further comprising:
a temperature sensor responsive to a temperature of the flowing gas hydrate.

19. The pipeline system of claim **1**, further comprising:
a controller configured to control a pressure or temperature of the flowing gas hydrate in response to a sensed pressure or temperature of the flowing gas hydrate.

20. A method implemented in a transportation pipeline system, the method comprising:
flowing a natural gas hydrate from a first geographical location to another geographical location through a transportation conduit of the pipeline system;
flowing a heat-transfer fluid between the first geographic location and the second geographic location through a cooling conduit of the pipeline system, the transportation conduit being disposed exterior to the cooling conduit; and
maintaining the flowable natural gas hydrate within a target temperature range during its transit of a portion of the pipeline system using refrigeration powered by combustion of natural gas decomposed from the flowable natural gas hydrate transiting the portion of the pipeline system, the target temperature range predicted to provide a selected stability of the flowable natural gas during its transit of the portion of the pipeline system.

21. The method of claim **20**, wherein the refrigeration is powered at least in part by combustion of natural gas released by decomposition of the flowable natural gas hydrate occurring in the normal course of transiting the portion of the pipeline system.

22. The method of claim **20**, wherein the refrigeration is powered at least in part by combustion of natural gas intentionally withdrawn and decomposed from the natural gas hydrate transiting the portion of the pipeline system.

23. The method of claim **20**, wherein the target temperature range provides a selected flowability of the natural gas hydrate, and is at least partially based on the stability temperature and pressure phase relationship for the particular natural gas hydrate transiting the portion of the pipeline system.

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